3. Internal Components

3.1 INTRODUCTION

This chapter covers the major air cleaning components used in nuclear ventilation and air cleanup systems, including HEPA filters, prefilters for HEPA filters, gas adsorbers, and demisters. It reviews the characteristics, construction, and application of these components including limitations and problems in their use. Other types of air and gas cleaning equipment are beyond the scope of this handbook.

3.2 HEPA FILTERS

HEPA filters [also called absolute, super-interception, very-high-efficiency, extreme efficiency, AEC (Atomic Energy Commission), and CWS (Chemical Warfare Service) filters] have proven to be the most effective, reliable, and economical devices for removing low concentrations of submicron particles at extremely high ($\geqslant 99.97\%$) collection efficiency. By definition,[1] a HEPA filter is a "throwaway, extended-medium, dry-type" filter having (1) a minimum particle removal efficiency of no less than 99.97% for 0.3-μm particles, (2) a maximum resistance, when clean, of 1.0 in.wg when operated at rated airflow capacity, and (3) a rigid casing extending the full depth of the medium (Fig. 3.1).

3.2.1 Performance Characteristics

Efficiency and Resistance. The Institute of Environmental Sciences (IES) standard for HEPA filters, CS-1,[1] lists three classes of HEPA filters with respect to performance: type A, which are tested for overall penetration (i.e., 100 minus percent efficiency) at rated flow only; type B, which are tested for overall penetration at rated flow and also at 20% of rated flow, with the filter encapsulated to disclose casing leaks; and type C, which are scanned filters. Scanning is a special leak test usually employed for filters used in clean rooms and clean benches but is generally not used for nuclear applications. Type A

filters are recommended primarily for use in recirculating air cleanup systems. Type B filters are efficiency-tested at both 100% and 20% of rated flow to disclose pinhole leaks that may not show up in the 100% flow test. Type B filters are recommended for most nuclear applications, particularly in once-through systems. The ERDA Quality Assurance Stations that test HEPA filters will make either the single-flow or two-flow test, as specified by the user.

The measured particle-collection efficiency[2] of most HEPA filters that are individually tested by
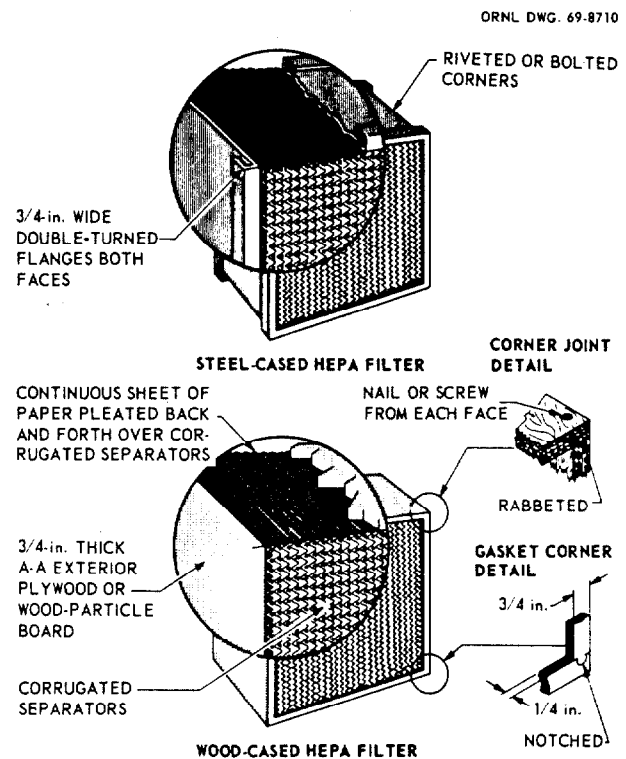
Fig. 3.1. Construction of open-face HEPA filter.

these stations is currently close to 99.99%. The value actually reported is penetration (100 minus percent efficiency). Penetration, resistance, and airflow capacity are determined at the same time and are marked on the case of each filter unit.

The penetration and airflow resistance of each HEPA filter unit are determined by the manufacturer before it is shipped from the factory, using procedures that were developed by the U.S. Army, U.S. Navy, and AEC (now ERDA). Most ERDA facilities require a confirmation test by one of the quality assurance stations (at either Oak Ridge, Tennessee; Richland, Washington; or the Rocky Flats Plant, Golden, Colorado) as a condition of acceptance. This confirmation test is an important quality control factor and is recommended to nongovernment organizations. The service is available to industrial and utility organizations, from ERDA, at cost plus 15% ($13.50 for a 1000-cfm filter in 1975, with a minimum charge of $135.00).[3] Efficiency tests are made with a monodisperse, thermally generated DOP aerosol having a count-median droplet diameter of 0.3 ± 0.03 μm in equipment of the type shown in Fig. 3.2.

Size and Airflow Capacity. The dimensions shown in Table 3.1 have been standardized for HEPA filters used in nuclear service. Other sizes can be obtained but should be considered as specials. Although the $24 \times 24 \times 5^{7}/_{8}$ in. size is included, it is structurally weak and should be avoided. The airflow capacities shown are nominal for the specified maximum resistance of 1 in.wg. Although some

manufacturers claim substantially higher airflows at this resistance, the values shown in Table 3.1 should be used for design purposes. The use of higher design airflow could create future logistic problems for the user and could result in lower-than-expected system performance if filters of different manufacture should be substituted at a future date.

Resistance. The standard resistance of a HEPA filter is 1 in.wg maximum when new and operated at rated airflow capacity. Resistance increases with dust[4] loading.

Dust-Holding Capacity. Dust-holding capacity of a filter in an actual situation is a function of the type, shape, size, density, "stickiness," and concentration of dust particles to which it is exposed. For HEPA filters it is often not an important factor since they will be protected by prefilters, particularly in high-dust-concentration applications. The HEPA filter will hold a considerable quantity of fine granular dust, but fibrous dust and lint tend to bridge the space

Table 3.1. Standard HEPA filters

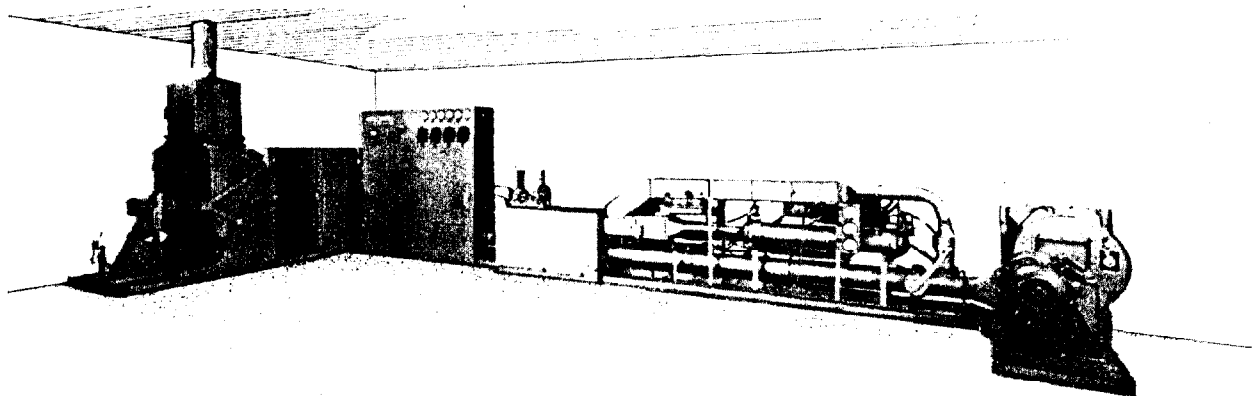| Face dimensions (in.)	Depth, less gaskets (in.)	Design airflow capacity at clean-filter resistance of 1.0 in.wg (scfm)
24 × 24	$11^{1}/_{2}$	1000
24 × 24	$5^{7}/_{8}$	500
12 × 12	$5^{7}/_{8}$	125
8 × 8	$5^{7}/_{8}$	50
8 × 8	$3^{1}/_{16}$	25

Fig. 3.2. Q-107 penetrometer used for efficiency testing of 1000-cfm HEPA filters by the manufacturer and ERDA Quality Assurance Stations. Courtesy Air Techniques, Inc.

between pleats, thus decreasing the filter's dust-holding capacity. Fibrous and flake-like particles comprise a substantial portion of atmospheric and "people-generated" dust. Dust-holding capacity has a bearing on filter life, however, and for design purposes is generally considered to be 4 lb per 1000 cfm of rated capacity. This is a conservative value for granular dusts. Actual life under service conditions can be determined only from simulation tests under comparable operating conditions or from experience.

3.2.2 Construction

Figure 3.1 shows typical construction of wood-cased and steel-cased open-face HEPA filters. The core (i.e., filter pack) is generally made by pleating a continuous web of fiberglass paper (the medium) back and forth over corrugated separators that add strength to the core and form air passages between the pleats. The core is sealed into a full-depth wood or steel casing (frame) with an elastomeric adhesive or polyurethane sealant. An alternative core construction of one manufacturer is made by wet-forming the medium into corrugations and pleats as it comes off the papermaking machine, thereby providing the necessary air passages and core structure without the use of separators. As of March 1976, this is the only domestic separatorless HEPA filter construction that is capable of meeting the specified minimum over-pressure resistance of 10 in.wg. In fact, this filter has been shown to be capable of withstanding over twice this pressure load without damage.

Medium (Filter Paper). HEPA filter papers are composed of very fine (submicron diameter) fibers in a matrix of larger diameter (1 to 4 μm) fibers. An organic binder is added to hold the fibers during the papermaking process and to give added paper tensile strength. All fire-resistant papers are made from glass fibers, sometimes with a small percentage of asbestos added to improve resistance to hydrogen fluoride. Tensile strength of the paper is sharply reduced (about 50%) at temperatures above 400°F due to burnout of the binder.[5] Minimum properties for HEPA filter papers are given in Appendix A (sample specification ACES-1) and in Military Specification MIL-F-51079.[6] Combustible papers, made from a mixture of cellulose and asbestos fibers, are no longer made. A special corrosion-resistant medium, developed for improved resistance to hydrogen fluoride, has been demonstrated but is not yet commercially available. This paper is fragile, and filters made from it must be handled with care to avoid damage.

Separators. Corrugated separators are interleaved with the pleats of the filter medium to space the pleats, thus forming airways, and to add strength to the assembled filter core. Separators of fire-resistant filters (Construction Class 1, IES CS-1)[1] are made from very hard (H-19 temper) 0.0015-in.-thick corrugated aluminum foil or from corrugated water- and corrosion-resistant asbestos paper. Kraft paper and other combustible materials, often used for separators of clean room and clean bench HEPA filters, are not permissible for nuclear grade filters. Plastics have been used for corrosion resistance by some manufacturers but are generally not suitable, because the corrugations often flatten at only moderately high temperatures (90 to 110°F), thus permitting the filter core to collapse and subsequently blow out if exposed to even design airflow. Minimum properties for separator materials, including corrosion resistance, are given in Appendix A (sample specification ACES-1).

Sealant. The sealant traditionally used to seal the filter core into the case is a heat- and moisture-resistant elastomeric adhesive. Some manufacturers use a chemically expanded self-extinguishing urethane foam. Filters that will be operated continuously at high temperature (above 400°F) are sealed with compressed glass-fiber matting or refractory adhesives. The sealant must (1) be moisture- and corrosion-resistant, (2) not deteriorate excessively under exposure to radiation or lose its resilience under alternating exposure to heat and cold or to dry or humid air, (3) not crack or delaminate from the frame at high temperature (5 min at up to 750°F), and (4) maintain a reliable seal between the filter core and casing under continuous service at design operating conditions. The high-temperature sealants do not meet all of these criteria, and their use, except in very special circumstances, is not recommended. Glass-fiber matting may not maintain a reliable seal at high temperature, silicone sealants delaminate quickly at only 10 or 20°F above their rated temperatures, and refractory sealants are extremely brittle after heating.

Case (Frame or "Cell Sides"). The usual case materials are fire-retardant exterior-grade plywood or wood-particle board and cadmium-plated or chromized carbon steel. Thicknesses of ¾ in. for wood and No. 14 U.S. gage for steel are required for rigidity and to resist the compressive loads imposed when the filter is clamped to a mounting frame (axial compressive loads of 400 psi, or higher, may be encountered in service). Grade A-A plywood has previously been specified to avoid manufacturing

errors, but the current shortage of plywood sometimes makes necessary the use of wood-particle board or lesser grades of plywood; wood-particle board is usually used today. When a lesser grade of plywood is permitted, the ply adjacent to the filter core must be sound (grade A, if possible) and must be coated completely with sealant to prevent lateral air leakage through the case. Exterior grade is specified for both plywood and wood-particle board to provide adequate moisture resistance. A minimum density of 45 lb/ft^3 and impermeable coating of both faces is specified for wood-particle board to ensure adequate impermeability and strength. Panels (four are required) for steel filter cases are cadmium-plated after all shearing and forming operations are complete. Because of shortages and restrictions on the use of cadmium, chromized steel is more widely used today. Chromized steel has been shown to have better corrosion resistance than either cadmium- or zinc-plated (galvanized) steel,[8] and cost is comparable. Chromized steel is a titanium-stabilized carbon steel with a diffusion-bonded chromium coating on each face. Steel cases should be used where continuous wetting or high humidity [>90% relative humidity (RH)] at high temperatures (>90° F) can be expected. Wood-particle board, in particular, swells considerably when exposed to excessive moisture.

Gaskets. Gaskets are critical items. Tests have shown that excessive variation in gasket thickness, poorly formed gasket corners, and improperly glued gaskets result in air leakage that exceeds the acceptance level of the filter.[9] If the gasket material is too hard, excessive bolt loading may be required to properly seal the filter to the mounting frame, thus resulting in possible filter damage. If the gasket material is too soft, excessive compression-set may take place, thus resulting in air leakage as clamping bolts and casing materials relax or expand under service conditions. Flat ($^5/_8$ to $^3/_4$-in. wide by $^1/_4$-in. thick) gaskets made from ASTM D1056 grade SCE 43 closed-cell neoprene sponge with cut surfaces on both faces are recommended. Gaskets are usually made in strips ($^3/_4$ by $^1/_4$ in.) with notched or dovetailed corners as shown in Fig. 3.1. Gaskets must be carefully aligned so they do not extend beyond the edges of the case flanges.

Because silicone mold-release compounds used in the manufacture of gasket material may prevent the adhesive from making a good bond with the neoprene, cut surfaces should be specified.

Gasket Adhesives. Fire-retardant rubber-base adhesives are used for gluing gaskets to the case.

Since the gasket is completely constrained once the filter has been installed, the chief requirement on these adhesives is that they hold the gasket firmly until the filter is installed.

Configuration. Rectangular and cylindrical HEPA filters are available in both open-face and enclosed configurations. Figure 3.1 shows open-face construction. The enclosed filter (Fig. 3.3) is similar except that the case is longer and closed, with nipples for attachment of the filter to the ducts. The casing of the enclosed filter is part of the system pressure boundary. Currently available enclosed filter units cannot meet the fire- and hot-air resistance requirements of UL-586,[10] nor do wood-cased enclosed filter units meet the rquirements of NFPA 90A.[11] Steel-cased enclosed filters, because of their bolted or riveted corners, generally leak under service conditions; therefore, acceptance tests of steel-cased units should specify encapsulation to ensure freedom from corner leaks. Enclosed filters generally have higher airflow resistance than open-face filters because of the restriction caused by the nipples. Cylindrical filters often seem to be an ideal solution to some design problems. However, because experience with them has often been poor and because they cannot be qualified for fire resistance under UL-586, they are generally not recommended.
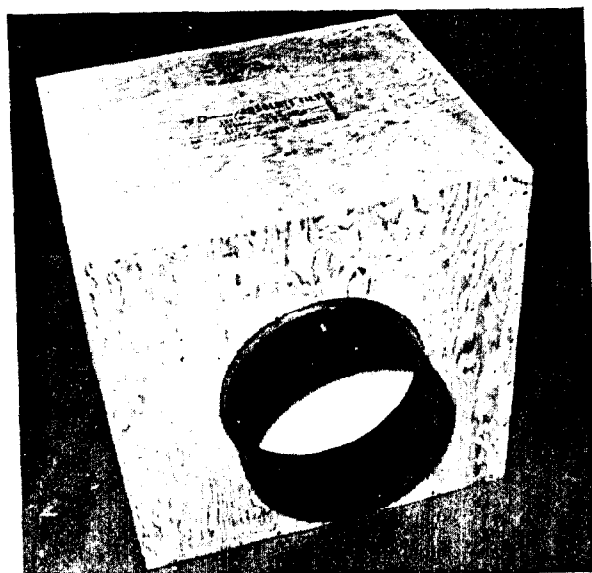

Fig. 3.3. A 1000-cfm wood-cased enclosed HEPA filter. Courtesy Cambridge Filter Co.

3.2.3 Weight of HEPA Filters

The weight of filter elements is an important factor in design and maintenance. Table 3.2 gives the clean-filter weight of open-face and enclosed rectangular models. Dirty-filter weights, for design purposes, are approximately 4 lb more per 1000 cfm of rated capacity.

3.2.4 Mechanical Properties

Other factors (heat, moisture) being equal, wood-cased filters are preferred to steel-cased filters because of their greater rigidity, superior vibration-damping characteristics, greater corrosion resistance, and greater corner strength.[6] Common practice in nuclear plant exhaust systems is to compress filter gaskets by 80% or more. This amount of gasket compression requires a clamping force of at least 18 lb per square inch of gasket surface, or a total load of 1250 lb or more on the frame of a 1000-cfm filter unit. Because its section modulus is nearly 20 times that of a steel case, the wood case is better able to withstand such high compressive, axial loads on the case panels. The wood case, with properly constructed (rabbeted) corners, also has about twice the corner strength of a steel case of the same size and is therefore better able to withstand racking or skewing when subjected to a force couple. Racking, which frequently occurs during handling, shipping, and installation, can damage either the filter medium or the seal between the core and case, or both. Face guards, consisting of hardware cloth or expanded-metal screens fastened to each face of the filter, increase the resistance to racking or skewing.

Resistance to shock pressures is important in a HEPA filter because it is often the final barrier between the contaminated space and the atmosphere. The shock overpressure resistance of open-face rectangular filters, based on tests by the U.S. Navy,[12] is given in Table 3.3 and Fig. 3.4. The recommended values are the maximum shock overpressure that the filters should withstand without visible damage or loss in filtration efficiency when exposed to a shock of approximately 50 msec duration. Filters with face guards on both faces have about 40% greater shock resistance than those without. Dirt-loaded filters in the Navy tests exhibited about 15% less shock resistance than clean filters. At overpressures of 0.5 to 1.0 psi greater than the failure value, the filter medium burst on the downstream side of the pleats; at overpressure of 2 psi greater than the failure value, extensive damage to the core occurred; and at 5 psi, blowout of the entire filter core occurred.[12] The greater shock resistance of filters with face guards is significant. The AEC, and more recently ERDA and NRC, has long advocated face guards on HEPA filters to minimize damage to the fragile core during handling and installation. The additional factor of higher shock overpressure resistance gives added weight to this recommendation. The shock overpressure resistance of enclosed filters is probably less than that of open-face filters, because the shock loading will be concentrated at the center of the core. However, no tests have been made to verify this phenomenon.

Another important property of HEPA filters is their ability to withstand continuous overpressure. By

Table 3.2. Weight of unused HEPA filters

Filter size (in.)	Nominal airflow capacity (cfm)	Approximate weight (lb) of filters with —	
		Wood case	Steel case
Open-face			
8 × 8 × 3$\frac{1}{16}$	25	2	3
8 × 8 × 5$\frac{7}{8}$	50	3.6	5.8
12 × 12 × 5$\frac{7}{8}$	125	4.8	7.3
24 × 24 × 5$\frac{7}{8}$	500	17	22
24 × 24 × 11$\frac{1}{2}$	1000	32	40
Enclosed			
8 × 8 cross section	25	5	9
8 × 8 cross section	50	7	10.5
12 × 12 cross section	125	17	20
24 × 24 cross section	500	64	72
24 × 24 cross section	1000	78	95

Table 3.3. Shock overpressure resistance of open-face HEPA filters

Filter dimensions (in.)		Overpressure at failure[a]	Recommended design limit for used filters	
Face	Depth		With face guards	Without face guards
8 × 8	$3\frac{1}{16}$	3.7	[b]	2.0
8 × 8	$5\frac{7}{8}$	4.5	[b]	2.5
12 × 12	$5\frac{7}{8}$	3.6	[b]	2.0
24 × 24	$5\frac{7}{8}$	2.2	1.7	1.2
24 × 24	$11\frac{1}{2}$	3.2	2.7	1.8

Overpressure (psig) column spans the three overpressure columns.

[a]Clean filter with 4- by 4-mesh face guards on both faces.
[b]Face guards not available.

Source: W. L. Anderson and T. Anderson, "Effect of Shock Overpressure on High Efficiency Filter Units," *Proc. 9th AEC Air Clean. Conf.*, USAEC Report CONF-660904, 1966.

specification, new HEPA filters must have sufficient structural strength to withstand a continuously applied overpressure of 10 in.wg, or higher, for at least 15 min without visible damage or loss of efficiency. For used filters, a value of 8 in.wg is recommended for design or planning purposes. In addition, the filter should be able to withstand the considerably higher, but short duration, over-pressures that might be encountered in a tornado or when a damper inadvertently slams shut in the duct system. Although the design basis tornado specifies an overpressure of 3 psi for a period of 3 sec,[13] it is unlikely that the HEPA filters would be subject to such a condition because of the attenuating effects of the stack, ductwork, and fans. Tests at Los Alamos showed that an 8 × 8 × $3\frac{1}{16}$ in. HEPA filter could withstand a 9-sec pressure pulse during which the maximum pressure of 3 psi was held for 3 sec without visible damage or reduction in efficiency.[14] Comparison of these results with the data of Table 3.3 indicates that the 24 × 24 × $11\frac{1}{2}$ in. filter can probably withstand a 9-sec pressure pulse of 2.5 psi, which is probably substantially worse than what the filter would experience in the event of a tornado.
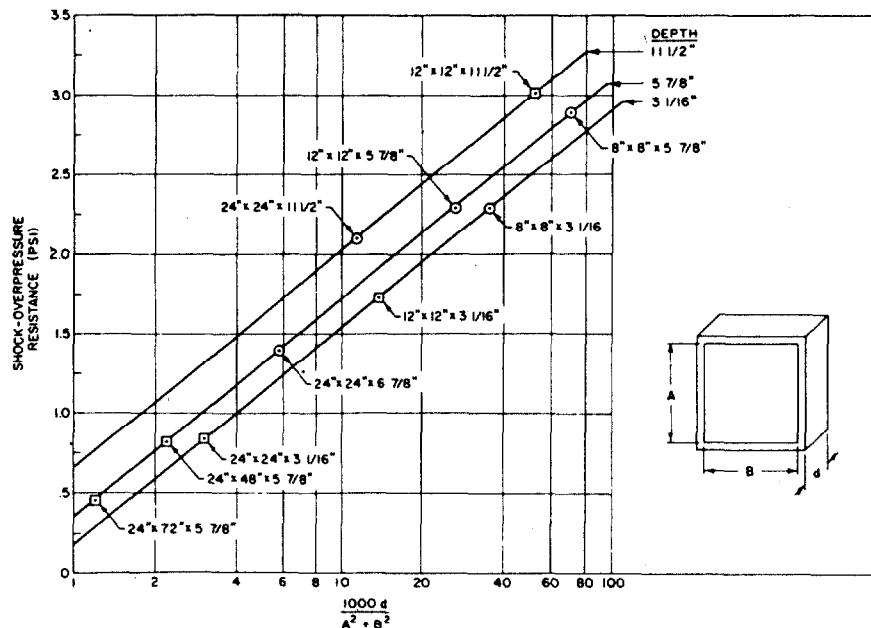

Fig. 3.4. Shock-overpressure resistance of clean HEPA filters (separator type) as a function of size. From C. A. Burchsted, "Environmental Properties and Installation Requirements of HEPA Filters," *Proc. Symp. Treat. Airborne Radioact. Wastes*, International Atomic Energy Agency, Vienna, 1968.

3.2.5 Fire Resistance

Standard IES CS-1[15] lists three grades of filter with respect to fire resistance: (1) fire resistant (made from fire-resistant or fire-retardant materials throughout), (2) semicombustible (having a fire-resistant medium but combustible separators and case), and (3) combustible (having flammable medium, separators, and case). Although grade 3 (combustible) filters are no longer available, they were previously used in the collection of process effluents that could be recovered by incineration of the filters and in applications where corrosive fumes would destroy fiberglass filter medium. Only fire-resistant (grade 1) filters are permitted in nuclear exhaust applications.

Fire-resistant HEPA filters are qualified and labeled by Underwriters' Laboratories.[10] The qualification test requires that the filter withstand (1) 700 to 750°F air for 5 min at rated airflow capacity with no significant reduction of filtration efficiency and (2) a spot-flame test in which a Bunsen burner flame is played on the filter core with no afterburning when the flame is removed. For sizes not specifically covered by UL-586, the buyer should specify filters of the same materials of construction as filters that have been qualified. Both wood- and steel-cased filters in the rectangular open-face configuration can be made to meet the requirements of UL-586; enclosed and cylindrical filters are qualified by the UL-586 test.

3.2.6 Environmental Properties

Hot Air Resistance. Tables 3.4 and 3.5 give limiting continuous service temperatures for wood- and steel-cased HEPA filters, based on sealants commonly used for sealing the core into the case. Filters with both types of case are designed to withstand temperatures to 750°F for 5 to 10 min. Continuous operation at high temperature is limited primarily by the sealant. At temperatures well below the char or "checkering" point, elastomeric sealants lose their shear strength (from about 850 psi at room temperature to as low as 15 psi at 300°F). The buyer should determine the manufacturer's limiting continuous service temperature if continuous operation at high temperature is necessary (see discussion of sealants in Sect. 3.2.2).

Moisture and Corrosion Resistance. The HEPA filter has limited resistance to corrosion. The separators, which must retain their shape to prevent collapse of the filter core, are the elements most subject to attack. Of the common separator materials, treated asbestos has the best corrosion resistance but has almost no moisture resistance unless specially treated. Aluminum has excellent moisture resistance and adequate corrosion resistance to the low concentrations of acids and caustics encountered in most applications. Plastic separators (polystyrene, polyvinyl chloride) are generally not suitable for nuclear applications because of their poor heat resistance; more importantly, the corrugations of plastic separators tend to flatten out when exposed to warm (90 to 120°F) air, thus resulting in a decrease of filter core strength. Stainless steel separators are unavailable because of filter manufacturing problems introduced by this material. If treated asbestos is specified, it must be qualified for exposure to the corrodents expected in service, because, if the coating is destroyed, the separator will collapse if exposed to moisture. A standard qualification test for moisture and corrosion-resistant separators has been developed.[16]

Wood casings are more resistant to chemical attack than cadmium-plated steel casings. However, wood is not suitable for extended continuous operation (seven days or more) in very humid (95 to 100% RH) environments at temperatures higher than 130°F, particularly when periods of operation at service temperature will alternate with periods of shutdown at room temperature. Under these conditions, moisture condensed on the casing surface may infiltrate the wood, softening and releasing fibers beneath the sealant, which may cause a failure of the seal or even complete release of the filter core. Wood-cased filters should not be used in very dry (<1% RH) environments. When steel cases are required, either chromized steel, "muffler grade" stainless steel (e.g, Type 409), or cadmium-plated carbon steel is recommended. Galvanized or zinc-plated carbon steel is not recommended. Austenitic stainless steels have been used for filter cases but are very costly and not warranted because of their throwaway nature. Reclamation of stainless steel cases, a process attempted by one ERDA contractor, proved impracticable because of the high cost of decontaminating the reclaimed cases. Wood-cased filters are not recommended for use in extremely dry air or inert gas (1 or 2% RH or less) because the wood will deteriorate.

The glass-fiber filter medium has fair resistance to corrosion and deterioration by water. However, glass, and therefore most fiberglass media, have poor resistance to hydrogen fluoride (HF). An HF-resistant medium has been developed by the Herty

provide excellent protection from water in systems where exposure to spray or to condensing steam is possible, particularly when this may be coupled with high levels of radiation.

Resistance to Plugging. Because HEPA filters are excellent collectors of very small particles, they are likely to plug when subjected to high loadings of sensible moisture, dust, or smoke. Dust plugging can be reduced by the use of effective prefilters, and moisture plugging can be minimized by the use of demisters. Demisters must be effective against very small droplets (at least down to 1 to 10 μm) because tests[19] have shown that exposure of HEPA filter media to radiation and to air pollutants such as soot and nitrous oxides may significantly reduce water repellency and, therefore, wet strength. As of March 1976, there is still no satisfactory device to protect the HEPA filter against the extremely high concentrations of particulate matter produced by a fire. Prefilters help to remove smoke but they may also plug rapidly and contribute to reduced airflow in the system; when resistance of the prefilter reaches an excessive value, the prefilter ruptures and the HEPA filter downstream is then exposed to the full concentration of smoke, which leads to its eventual plugging and probable rupture. Because rupture of the HEPA filter constitutes a breach of containment, some practical means of suppressing smoke before it reaches the filter system is required. Studies of smoke plugging are being made by ERDA, and means of alleviating the problem will be recommended as the studies progress.[20]

3.2.7 Costs

Table 3.6 gives relative costs of various open-face HEPA filter constructions. Commercial costs of 1000-cfm HEPA filters, at the time this handbook is published, are about $80 to $120, depending on discounts and quantity purchased.

Table 3.6. Relative costs of various HEPA filter constructions

| Casing material | Separator material | | | |
	Untreated asbestos	Aluminum foil	Treated asbestos[a]	Plastic
Wood	1.00	1.02	1.08	1.71
Carbon steel[b]	1.13	1.16	1.22	1.89
Stainless steel	1.96	1.99	2.04	2.69

[a] Qualified for moisture and corrosion resistance in accordance with procedures established by ERDA.

[b] Cadmium-plated or chromized.

3.3 PREFILTERS

3.3.1 Classification

Air filters used as prefilters and as building supply-air filters in nuclear facilities are classified as shown in Table 3.7. The classification is based on arrestance (weight percent) and dust-spot (stain) efficiency as determined by ASHRAE 52-68.[21] ASHRAE 52-68 requires both a dust-spot (i.e., stain) efficiency test made with atmospheric dust and a synthetic-dust weight arrestance test. The standard emphasizes the correct use of, and distinction between, the two terms; and to avoid confusion, it requires that both values be tested and reported. Table 3.7 shows typical values for the two tests.

By comparison, a HEPA filter has an ASHRAE atmospheric dust-stain efficiency of 100%. Because the atmospheric dust-stain test is based on the staining capacity of the dust that penetrates the filter, compared to the staining capacity of the entering dust, it is not a true measure of particle-removal efficiency for any given particle size range. Table 3.8 gives a more meaningful comparison.

3.3.2 Performance

The performance of air filters is defined by particle-removal efficiency, resistance to airflow (i.e., pressure drop), airflow capacity, and dust-holding capacity. To understand manufacturers' rated efficiencies, it is important for the buyer to know what test method was used; whether the reported efficiency refers to weight, stain, or particle count; what test dust was used; and whether clean-filter efficiency or average efficiency over the projected life of the filter is reported. Three test methods were formerly used for rating group I, II, and III filters: the Air Filter Institute (AFI) weight method,[22] the AFI method,[23] and the National Bureau of Standards (NBS) dust-spot method.[24] Although these tests have been replaced by ASHRAE 52-68,[21] they are still used occasionally. In general, the results obtained with the older tests are comparable to those of the respective parts of ASHRAE 52-68.

ASHRAE 52-68 has two basic efficiency tests—a synthetic-dust weight arrestance or weight test, and an atmospheric dust-spot efficiency test. The weight test determines the percent of a synthetic dust that is collected by the filter during an accelerated test. As Table 2.4 shows, more than 97% of the particles in a typical air sample are larger than 1 μm on a weight basis, whereas on a count basis over 99.99% are

Table 3.7. Classification of common air filters

Group	Efficiency	Filter type	Stain test efficiency (%)	Arrestance (%)
I	Low	Viscous impingement, panel type	<20[a]	40–80[a]
II	Moderate	Extended medium, dry type	20–60[a]	80–96[a]
III	High	Extended medium, dry type	60–98[b]	96–99[a]
HEPA	Extreme	Extended medium, dry type	100[c]	100[a]

[a]Test using synthetic dust.
[b]Stain test using atmospheric dust.
[c]ASHRAE 52–68, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Table 3.8. Comparison of air filters by percent removal efficiency for various particle sizes

Group	Efficiency	Removal efficiency (%) for particle size of –			
		0.3 μm	1.0 μm	5.0 μm	10.0 μm
I	Low	0–2	10–30	40–70	90–98
II	Moderate	10–40	40–70	85–95	98–99
III	High	45–85	75–99	99–99.9	99.9
HEPA	Extreme	99.97 min	99.99	100	100

smaller. Therefore, a filter with a high weight efficiency may be inefficient for removal of small particles.

The dust-spot tests are made by comparing the opacities of stains made on filter papers by air samples withdrawn from the test duct upstream and downstream of the filter. Because particles in the submicron range are chiefly responsible for staining the samples, even though they represent only a fraction of the total weight of dust charged to the filters, the test essentially measures the efficiency of the filter for small particles. However, because the atmospheric dust-spot test uses ambient air as the challenge, results depend on the nature of the atmospheric dust in the location where the tests are made.

The results of the various tests are not comparable, and an efficient filter by one test may be inefficient by another. The user should examine filter efficiency data very carefully to ensure that the precise meaning of the reported data is clear. Efficiency tests for group I, II, and III filters are made on prototypes only, and the results are extrapolated to the various filter sizes of similar design made by the same manufacturer. A predelivery test of each filter unit would be too costly and is not recommended. Table 3.9 gives the

comparative performance of group I, II, and III filters (average over the life of the filter to the manufacturer's recommended maximum pressure drop).

The values for dust-holding capacity are based on tests with a synthetic dust. Because actual dust-holding capacity varies with the nature and composition of the dust, the dust-holding capacity under service conditions cannot be accurately predicted on the basis of manufacturers' catalog data.

3.3.3 Construction

Panel Filters. Group I panel filters (viscous impingement filters) are shallow, tray-like assemblies of coarse fibers (glass, wool, vegetable, or plastic) or crimped metal mesh enclosed in a steel or cardboard casing. The medium is coated with a tacky oil or adhesive to improve retention of trapped particles. Throwaway, replaceable-medium, and cleanable-medium types of panel filters are available. The latter have metal mesh and are generally not used in contaminated exhaust service because of the difficulties and high labor costs associated with cleaning. Figure 3.5 shows typical throwaway and replaceable-medium types. Panel filters have fairly high dust-holding capacity, high airflow capacity with low resistance, and high removal efficiency for large particles. They are particularly effective against fibrous dust and heavy concentrations of visible particles but are useless for protection against submicron particulates. Except when large particles are present from a production operation such as grinding, panel filters are of limited value as prefilters for nuclear exhaust applications because of their limited effectiveness against small particles (5 μm and less) and because they are rapidly plugged by lint and other fibrous materials. Panel filters of the type shown in Fig. 3.5 have low initial cost and low operating cost, but they may be more expensive than

Table 3.9. Airflow capacity, resistance, and dust-holding
capacity of air filters

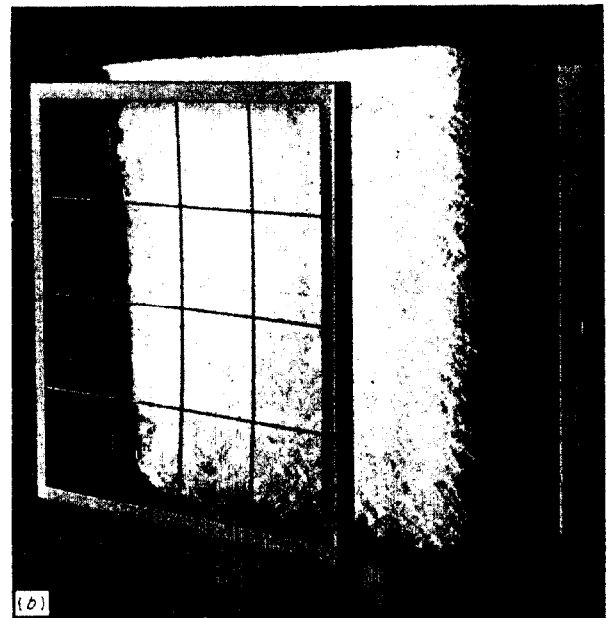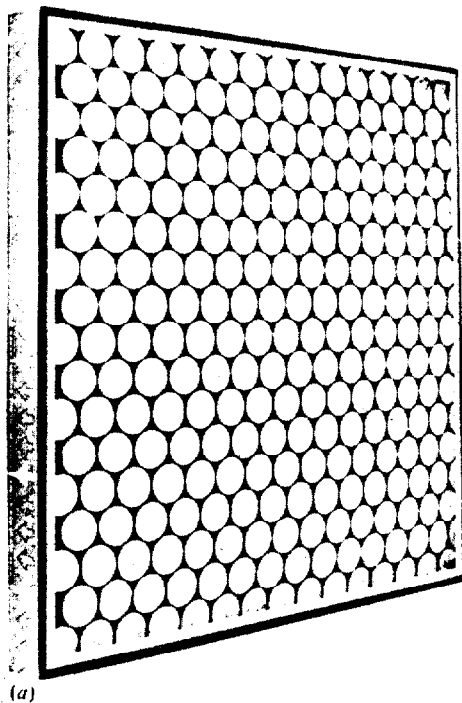| Group	Efficiency	Airflow capacity (cfm per square foot of frontal area)	Resistance (in.wg)		Dust-holding capacity (g per 1000 cfm of airflow capacity)
			Clean filter	Used filter	
I	Low	300–500	0.05–0.1	0.3–0.5	50–1000
II	Moderate	250–750	0.1–0.5	0.5–1.0	100–500
III	High	250–750	0.20–0.5	0.6–1.4	50–200

Fig. 3.5. Viscous-impingement panel-type group I air filters. (a) Throwaway paper-cased furnace filter; (b) replaceable-medium type.

an initially more costly group II or III filter that gives better protection to the HEPA filters.

Group II and III Filters. Group II (moderate efficiency) and group III (high efficiency) filters are extended-medium dry-type units. That is, the medium is pleated or formed as bags or "socks" to give a large surface area with minimum frontal area, and the medium is not coated with an oil or adhesive. Throwaway cartridge (Fig. 3.6), replaceable-medium (Figs. 3.7 and 3.8), and cleanable-medium types are available. The particle-removal efficiency of group II filters is moderate to poor for submicron particles but often approaches 100% for particles larger than 5 μm. In most cases the pressure drop of extended-medium filters varies directly with efficiency. Group II filters are recommended for high lint and fiber loading applications. The large area of the medium relative to frontal area permits the use of extended-medium filters at duct velocities equal to or higher than those permissible with panel filters. Group III filters are used when higher efficiency for smaller particles is desired, but their dust-holding capacity may be low relative to the lower efficiency group II filter.
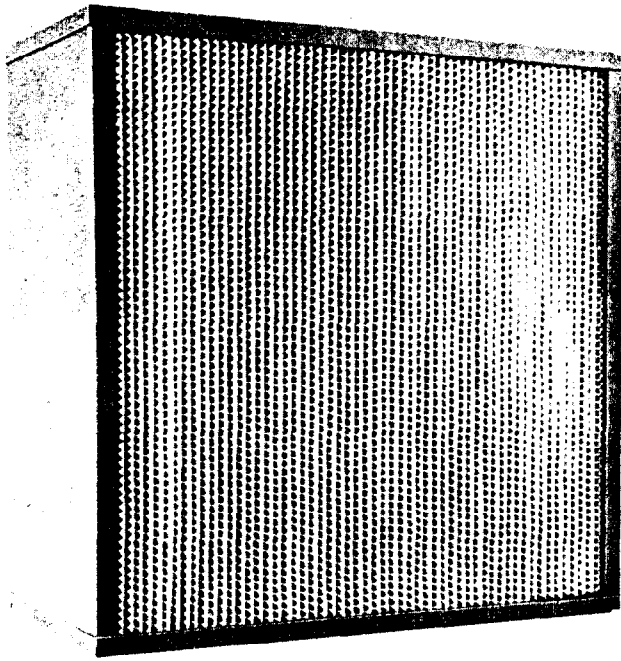
53

Fig. 3.6. Extended-medium dry-type throwaway, group III (high-efficiency) air filter with fiberglass medium, aluminum separators, and mineral-board case.

Fig. 3.8. Bag-type, replaceable-medium, group III (high-efficiency) ventilation-type air filter. Courtesy Cambridge Filter Corp.
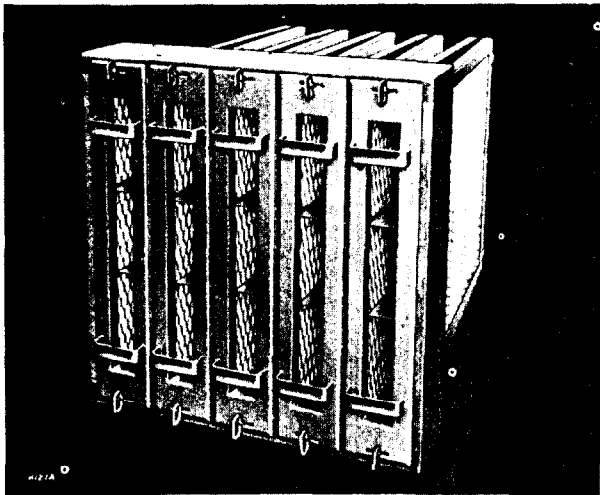

Fig. 3.7. Replaceable-medium, group III (high-efficiency ventilation-type) air filter with wire medium supports. Note individually removable core segments. Unit is 24 × 24 × ~30 in. deep. Courtesy American Air Filter Co.

3.3.4 Fire Resistance

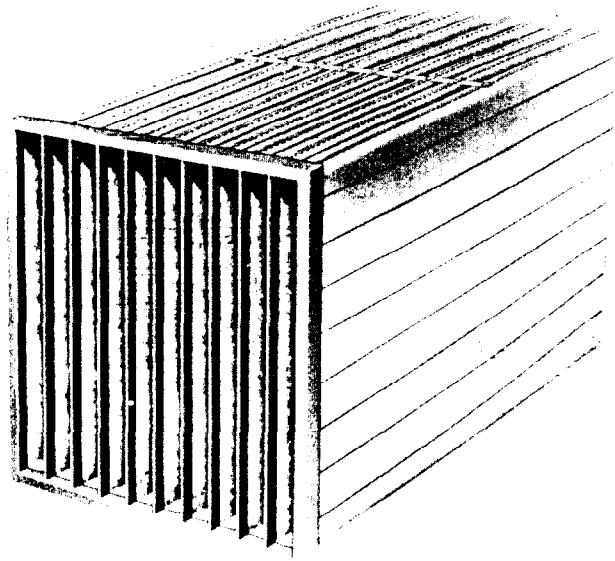Underwriters' Laboratories classifies common ventilation air filters in two categories with respect to fire resistance.[25] When clean, UL class 1 filters do not contribute fuel when attacked by flame and emit only negligible amounts of smoke. UL class 2 filters may contain some combustible material but must not contribute significantly to a fire. Because dust collected on either a UL class 1 or class 2 filter may burn vigorously and create a fire that is difficult to extinguish, the use of UL-rated filters should not lead to an unwarranted sense of security on the part of the user. Filters that meet the UL requirements are listed in the current UL *Building Materials List*.[26] NFPA 90A[11] makes the use of UL-rated filters mandatory.

3.3.5 Hot Air Resistance

Most types of common air filters are suitable for continuous operation at temperatures no higher than 150 to 250°F. Certain types with glass-fiber media in steel or mineral board casings may be used at temperatures as high as 400°F. With any high-temperature filter, the user should take a conservative view of performance claims, particularly for efficiency at operating temperature. The user should examine his application closely to determine if the filters will be exposed to continuous high temperature or if the high-temperature exposure will be intermittent or under emergency conditions.

3.3.6 Maintenance Considerations

Air filters may be classified by the method of medium renewal, that is, throwaway cartridge, replaceable medium, or cleanable medium. The first choice for nuclear exhaust applications is the throwaway cartridge. The filter shown in Fig. 3.6 is typical of this class. Replaceable-medium filters offer an advantage over throwaways in that the bulk of material to be disposed of is smaller. This may reduce handling and disposal costs (radioactively contaminated filters are usually buried at NRC-authorized burial grounds), but reentrainment of contaminated dust is possible as the medium is removed from the holding frame and crumpled up to be stuffed into a bag for disposal. Replaceable-medium designs, therefore, are not recommended for nuclear exhaust applications. Cleanable filters are unsatisfactory because they require a long downtime of the facility, and they require decontamination facilities adjacent to the filter house. Cleaning of filters transfers radioactive material from the filter to the contaminated liquid waste system, which may pose a more difficult problem than the disposal of dry throwaway units.

Corrosion and Moisture. The choice of filter type may be limited by corrodents and moisture in the air stream in which it is to operate. Many filter media will not withstand acid or caustic fumes; fiberglass will withstand exposure to most reagents except hydrofluoric acid or gaseous hydrogen fluoride. Aluminum parts (e.g., separators) may deteriorate in sea air or when caustic substances are deposited on them. Plastics have poor heat resistance and generally will not meet UL requirements. Heavy concentrations of water droplets or condensate may plug or deteriorate filters and result in frequent filter replacement. In general, common air filters that have equivalent construction to the HEPA filters used in the system will have equivalent moisture and corrosion resistance. Plugging as a result of moisture will not be quite so severe for class III filters and will probably be considerably less for class II and class I filters. Radiation resistance of common air filters has not been investigated.

Change Frequency. Pressure drop (resistance) is the primary factor in prefilter replacement. Replacement at the pressure drop suggested by the manufacturer is recommended. Panel filters will plug rapidly under heavy lint loads, whereas some lint, by breaking up the uniformity of the dust deposit, may be beneficial to extended-medium

filters. Extended-medium filters will plug rapidly in heavy concentrations of soot or smoke. Operation at airflow levels below the manufacturer's rated capacity extends filter life and reduces filter change frequency (see discussion of underrating, Sect. 2.3.6). On the other hand, when airflow exceeds the manufacturer's recommendations by more than about 15 to 20%, dust-loading rate (and consequently filter replacement costs) begins to increase exponentially with arithmetic increases in airflow.

3.3.7 Operational Considerations

The decision to use prefilters must be determined for each application on the basis of total air cleaning system costs and the consequences of exposing the HEPA filters to the environment without protection. In some cases, prefilters may double or triple the life of HEPA filters; in other cases, the increase may be insignificant. In general, HEPA filters should be protected from (1) particles larger than 1 or 2 μm in diameter, (2) lint, and (3) dust concentrations greater than 10 grains per 1000 ft^3. Resistance (and corresponding power costs), system installation costs, and filter element replacement costs generally increase with increasing prefilter efficiency. Table 3.10 shows the relative price ranges of filters usually used for prefiltering.

Table 3.10. Price indexes of common air filters per 1000-cfm capacity

Group	Efficiency	Type	Price index
I	Low	Panel, viscous impingement	1
II	Moderate	Extended medium	2–10
III	High	Extended medium	30–70
-	HEPA	HEPA	80–100

3.4 RADIOIODINE ADSORBERS

3.4.1 Introduction

The gas (i.e., adsorbate) of primary interest in nuclear air and gas cleaning systems is radioiodine. Although concentrations will be extremely low (probably no more than 1 μCi/ml, or about 8 μg/m^3, in the primary containment air of a reactor following a DBA), the high affinity of radioiodine for the thyroid makes it a major contributor to potential radiation doses to the public and plant personnel. Radioiodine may be in the form of elemental iodine (I_2) or organic iodine compounds, principally methyl iodide (CH_3I).

Adsorption on activated carbon is the most frequently used method for removing radioiodine from air and gas streams in large ventilation and air cleanup systems. Inorganic adsorbents, such as silver-exchanged zeolite, are sometimes used in small systems where high temperatures or the presence of contaminants, such as nitrogen oxides, which react with carbon make the use of activated carbon unadvisable. The high cost of inorganic adsorbents often makes their use unattractive for large systems.

Activated carbon is produced by first making a charcoal from coconut, nut shell, wood, bituminous coal, or petroleum sludge. This charcoal is then activated by controlled heating in a steam atmosphere to drive off organic matter and generate large internal surfaces on which adsorption can take place. The internal area of activated carbon ranges from 700 to 1800 m^2/g, based on the nitrogen gas isotherm by the BET method. The activated carbon may then be impregnated with chemicals, at this time principally I_2, KI, and triethylene diamine (TEDA), to enhance its ability to adsorb organic radioiodine compounds. Definitions of terms relating to adsorbents and activated carbon are given in ASTM D2652.[27]

3.4.2 Performance of Adsorption Systems

Important properties of a nuclear adsorption system are efficiency for trapping radioiodine, breakthrough capacity, ability to retain sorbed radioiodine, airflow capacity and velocity, resistance to airflow, and resistance to ignition. The remainder of this section discusses important performance considerations. The discussion is based primarily on activated carbon because it is the most widely used material. However, much of the material applies equally to zeolite and other inorganic adsorbents.

Efficiency. The efficiency of a nuclear grade adsorbent is the measure of its ability to remove (i.e., sorb) from a flowing air or gas stream an adsorbate of interest (i.e., I_2, CH_3I). The efficiency of activated carbon is a function of (1) the degree of activation, ash and moisture content, and impurities present in the carbon; (2) the type and quantity of impregnant; (3) granule size (efficiency varies inversely with average granule size); (4) gas residence time (i.e., the contact time between the gas and the carbon in the adsorber bed—at constant airflow velocity, efficiency increases with increasing gas residence time); (5) airflow velocity through the adsorber bed (at constant gas residence time, efficiency increases with

increasing airflow velocity); and (6) temperature and relative humidity of the air or gas stream (for activated carbons, efficiency tends to decrease with increasing temperature and relative humidity; for silver zeolite, efficiency increases with increasing temperature). Special high-purity low-ash grades of activated carbon are generally used for trapping radioiodine. Efficiency is determined by laboratory testing using radioactively traced iodine and methyl iodide.

Minimum efficiencies for elemental iodine and methyl iodide at low (70°F) and elevated (180°F) temperatures and low (70%) and high (>95%) relative humidity are specified in RDT M 16-1[28] and ANSI N509.[29] Trapping of elemental radioiodine involves physical adsorption only, and the efficiency of nearly any good grade of activated carbon, impregnated or not, will be at least 99% (DF = 100) under any combination of temperature and humidity that would be encountered in a nuclear air cleaning system. Trapping of organic radioiodine compounds, on the other hand, requires an impregnated carbon and involves physical adsorption, chemical reaction, and/or isotopic exchange. Efficiency for those compounds is dependent on temperature and relative humidity of the air or gas stream, and performance of the adsorbent must be qualified under a range of operating conditions as specified by RDT M 16-1.[28] The tests of RDT M 16-1 bracket the range of conditions that are likely to be encountered in most nuclear applications.

In addition to efficiency tests, qualification of a nuclear grade adsorbent requires a 4-hr, 180°C radioiodine desorption test and a number of physical properties tests that characterize the adsorbent from the standpoint of particle size, resistance to attrition, ignition temperature, and impregnation. Efficiency tests are very costly and are made only at the time a grade of product is qualified. If there is any significant change in base material, impregnation, or manufacture, however, the material must be requalified and a new grade designation assigned. Subsequent production lots of material are evaluated on the basis of (1) physical properties tests, the results of which must conform, within reasonable tolerances, to the values established at the time of qualification and (2) a 4-hr 180°C radioiodine desorption test. The radioiodine desorption test has been found very sensitive for differentiating between candidate products and for detecting changes or errors in manufacture. Substantial differences have been observed between ostensibly equivalent

products (e.g., penetrations of four KI–I$_2$ impregnated activated carbons, claimed to be equivalent to one another, ranged from 0.28% to 12.8% in the 4-hr 180°C radioiodine desorption test)[30] and, on occasion, between successive production lots of the same material. For this reason, the user should verify test results of production lots to satisfy himself that the product meets specification requirements. For conservatism, the efficiency values of Table 3.11 are recommended for design purposes. (These values are single-pass efficiencies, and the efficiency of a recirculating system would be multiplicative.)

Capacity. The capacity of a nuclear grade adsorbent is its breakthrough capacity, that is, the quantity of adsorbate (radioactive iodine or iodine compound) which, when charged to the adsorbent bed, results in the first appearance of the adsorbate in the effluent from the bed. Capacity is a function of the surface area of "active sites" in the adsorbent, and therefore of the depth and area of the beds. For impregnated activated carbons it is also a function of the nature, quantity, and condition of the impregnant.

Aging. Aging or weathering of activated carbon is the gradual deterioration of "active sites" due to oxidation of its surfaces or to desorption or chemical reaction (with environmental poisons) of its impregnant.[30] This deterioration results in decreases, with time, of capacity and efficiency, and thus affects the useful life of the carbon. There are currently no valid guides for estimating the useful life of activated carbon. Tests by the British in 1966, using coal-base activated carbon impregnated with KI and TEDA, indicated a life of 18 months in a continuously on-line system, 3 years in a standby (i.e., normally off-line) system, and 5 years for carbon kept in sealed

Table 3.11. Recommended design values for single-pass methyl iodide efficiency of full-scale adsorbers containing impregnated activated carbon

2-in. bed depth, 0.2-sec minimum gas residence time

Relative humidity	Percent efficiency for radioiodine as methyl iodide	
	70° F	270° F
85 or less	95	98
90	90	90
95	80	70
98	70	30

containers.[31] Experience in the United States with coconut-base and certain experimental coal-base carbons indicates much more gradual, but still significant, aging effects.[30,32] The numbers of the British tests can probably be ignored for practical purposes, but the ratio of the numbers is probably valid. That is, the carbon of a standby system can be expected to last about twice as long as the same grade of carbon when installed in a continuously on-line system. Therefore, test and experience data obtained from ERDA facilities with continuously vented containments can be extrapolated to the off-line system. Because of the uncertain life of activated carbon under normal operating conditions, NRC recommends that samples from ESF systems be taken for laboratory testing every 720 hr of fan operation. Installation of an elapsed time meter on the fan is recommended as a means of timing the withdrawal of test samples. Regulatory Guide 1.52 gives the requirements for laboratory testing of used carbons, using the test procedures but not the acceptance criteria of RDT M 16-1 for new carbons.[33]

The loss in capacity for elemental iodine is much slower than that for methyl iodide. Beds exposed continuously to flowing air at one installation showed adequate remaining capacity for elemental iodine after four years of service.[34] At other installations, however, exposure of the beds to paint and solvent fumes reduced capacity to the point that efficiency fell to unacceptable levels in only a few months.[35,36] The loss in breakthrough capacity indicates (1) a need for routine analytical tests on samples taken from the beds to determine remaining capacity; (2) a need for conservative adsorber design; and (3) the need to protect adsorbers from unnecessary exposure to moisture, hydrocarbons, and other poisons. There is no way to rejuvenate used carbon other than by complete reactivation, a process which is impossible for carbon that has been even slightly radioactively contaminated.[30]

The use of a sacrificial or guard bed in advance of the active bed to protect the active bed from "tramp" contaminants was suggested several years ago and is still recommended where cost permits.[37] The guard bed can be filled with a less expensive carbon and does not require costly leak tests. In any event, adsorbers should be protected against fumes, dust, and dirt during construction and maintenance operations or they may have to be replaced before startup. It is strongly recommended that, in construction situations, adsorbers not be installed until the system is ready for startup. During maintenance

operations, if the system is not required for decontaminating air of the contained space, the filter housing should be isolated by dampers.

Performance for organic compounds is severely limited if the carbon becomes wet, as would be the case in some types of reactors if adequate demisters and/or heaters were not provided. Flooding of carbon beds with water effectively destroys their capability for trapping iodine in any form and also results in the release of any radioiodine that has been trapped.[40]

Retention. Because adsorbers may have to be operated for several days or weeks following an upset or accident in the contained space served by them, consideration must be given to retention of trapped gases. The retentivity of a sorbed chemical is characteristically less than 35% of the breakthrough capacity.[38] So long as the quantity of iodine held in the bed is less than the retentivity limit and desorption temperature does not greatly exceed the adsorption temperature, desorption is not a significant problem. Some iodine loss will take place at higher desorption temperatures, particularly from impregnated carbons; these higher temperatures may also desorb some of the impregnant and further reduce the capacity for radioactive organic iodides. The extent of loss is still under investigation. The retentivity factor further emphasizes the need for conservative adsorber design.

High-temperature desorption is not a problem with silver-exchanged zeolites or silver-impregnated alumina because the iodine reacts with the silver to form a tightly bound chemical species, even at very high temperatures. These materials perform better at high operating temperatures, which is one reason why they are favored in certain applications.

Ignition Temperature. Adsorption systems containing activated carbon must be designed so that the decay heat generated by collected fission products cannot cause ignition of the carbon or overheating to the point of significant desorption of collected fission products or impregnant. The postaccident air cleanup system of a nuclear power reactor, for example, may contain several tons of carbon loaded in 2-in. deep to 6-in. deep beds. The only cooling method of consequence is forced air circulation. If, as is assumed for the DBA, 25% of the iodine inventory of the reactor core is released to the containment and is collected in the adsorption system during the first few hours following the accident, calculations and laboratory tests show that the ignition temperature

might be reached if airflow through the bed is reduced to less than 5 fpm. On the other hand, if adequate airflow can be maintained, there is little doubt that the heat from deposited radioiodine can be removed without causing ignition or significant desorption from the beds.[39] Calculational results by the computer program TOOHOT show that under certain conditions ignition of the carbon of an adsorber bed can take place at an airflow velocity of 4 fpm,[40] assuming that the high-ignition-temperature carbons specified in RDT M 16-1 are used.

The ignition temperature of new charcoal is a function of ash content, impurities, internal surface area, granule size, flammability of chemical impregnants, bed depth, and airflow through the bed.[41] Adsorbed substances (such as solvents and hydrocarbons) may further alter ignition temperature, which varies directly with the degree of activation and inversely with granule size. The lowest ignition point of new KI and KI_3 ($I_2 + KI$) impregnated coconutbase carbons is about 290°C.[42] The ignition of TEDA-impregnated carbons may take place at temperatures as low as 180 to 190°C, depending on the level of impregnation, airflow, and bed depth.[41,43,44] With conservative bed design (i.e., a bed that contains a large volume of charcoal relative to the airflow capacity of the system and to the amount of iodine to which it can be exposed), the specific loading of fission products will be low. This reduces the possibility of spontaneous combustion, assuming that an airflow in excess of 8 to 10 fpm can be maintained through the system.

Airflow Capacity and Resistance. Airflow capacity is a function of bed size, configuration, and resistance. Resistance is a function of the size of carbon granules (mesh size), packing density, bed thickness, free area of the granule retaining screens, and airflow velocity. For a given bed design, resistance varies directly with airflow velocity. On the other hand, efficiency of a given bed design, assuming a minimum gas residence time to effect sorption, varies inversely with airflow velocity. Operation above the rated capacity of the adsorber, therefore, is not recommended because of the possible reduction in efficiency, as well as the more obvious penalties of higher pressure drop and operating costs. Assuming there is no change in airflow velocity and that particulate filters are provided upstream to intercept dust that might otherwise collect on the screens or in the charcoal itself, pressure drop will remain constant over the life of the adsorber. For constant gas residence time, efficiency also increases with in-

creasing velocity; for a fixed bed depth in proportions that will maintain the gas residence time, therefore, efficiency can be enhanced by increasing the size of the bank and the airflow velocity.

3.4.3 Adsorber Unit Design and Construction

Nearly all adsorbers in current commercial facilities are either of the modular tray configuration shown in Fig. 3.9, which are installed in banks as shown in Fig. 3.10, or of a permanent single-unit (PSU) fill-and-empty-in-place (often called deep bed or gasketless) design similar to the unit shown in Fig. 3.11. The pleated 1-in.-bed modular cell shown in Fig. 3.12, although still used in a number of facilities, is obsolete. Minimum requirements for pleated-bed (type I) and tray (type II) cells are specified in IES CS-8.[45] Tray (type II) adsorber cells consist of two 2-in. thick adsorbent beds with an airspace between. Cross-sectional dimensions are standardized (IES CS-8), and the cell is installed in standardized openings (ref. 45, Appendix A) in the mounting frame of the housing. (Requirements for mounting frames are described in Chap. 5.) Length of the cell varies according to the manufacturer's particular design and may range from 26 to 32 in. It is recommended that the mounting frame have a cell support structure that can accept a cell length up to at least 32 in. to permit interchangeability with the cells of any manufacturer. Cells weigh between 80 and 100 lb, depending on the individual design, and contain from 47 to 52 lb of 8- by 16-mesh[46] activated carbon. No caulking, scrims, or other nonmetallic materials, except the neoprene gasket, are permitted in its

construction. The cell is designed for a gas residence time of 0.25 sec and resistance of 1.1 in.wg when operated at a volumetric airflow rate of 333 cfm. Air
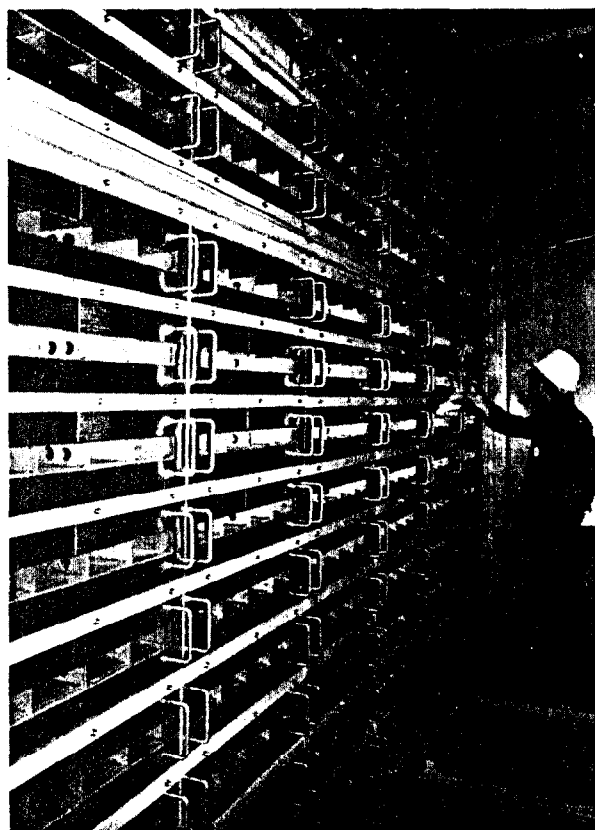

Fig. 3.10. Bank of type II adsorber cells in nuclear reactor system.
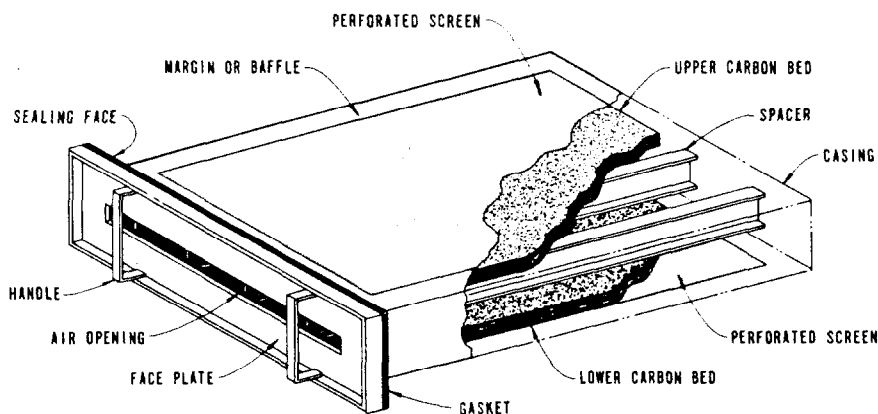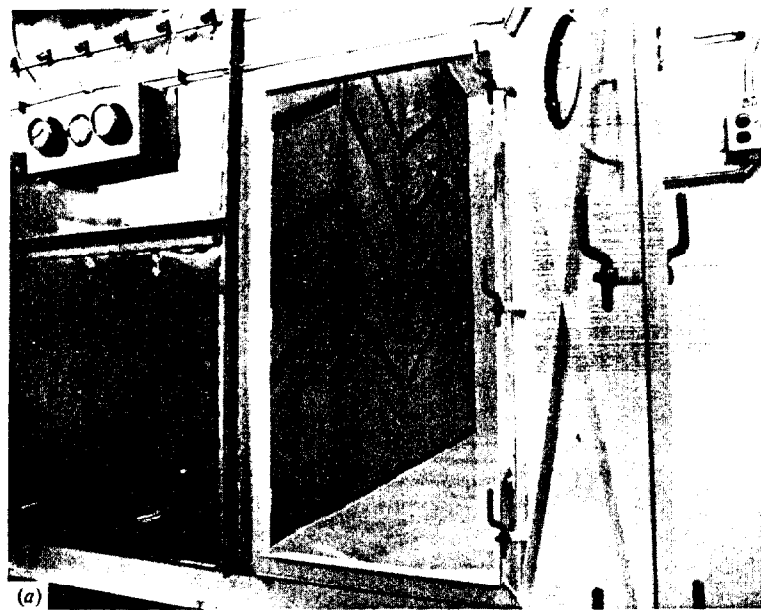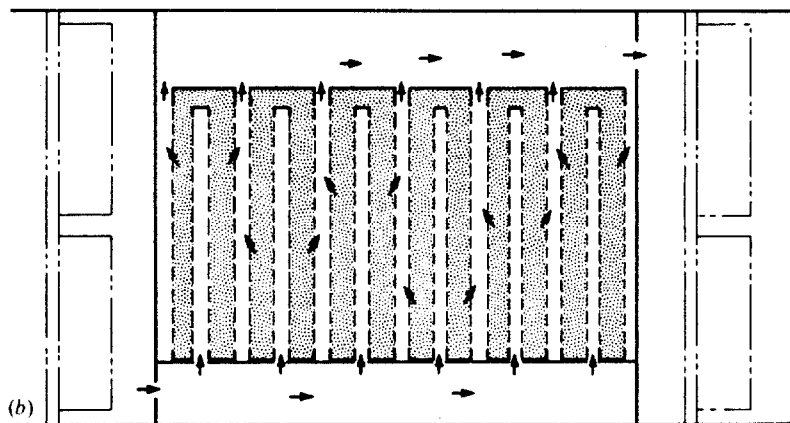
ORNL-DWG 72-7605

Fig. 3.9. IES CS-8 type II (unit tray or drawer type) adsorber cell. Weight, 80 to 100 lb.

ORNL-DWG 76-4687

Fig. 3.11. Permanent single-unit (PSU) adsorber. PSU adsorbers are permanently installed components that are filled and emptied in place through ports (not shown) on the top and bottom. Unit is all-weld construction with no gasket seals. (*a*) View of downstream face of inclined bed PSU adsorber unit. Courtesy CTI-Nuclear, Inc. (*b*) Airflow through typical vertical bed PSU adsorber. Note HEPA filters upstream and downstream. Courtesy CVI Corp.

can flow in either direction through the slot (i.e., the cells may be installed on either the upstream or downstream side of the mounting frame). Unit cells for nuclear service must be all stainless steel; carbon steel cells used in earlier installations corroded in only a few months when exposed to moisture and air carrying significant concentrations of nitrogen oxides or other corrodents. The type II cell is suitable for containing inorganic adsorbents (e.g., silver zeolite) in addition to activated carbon.

There are currently no standards for PSU adsorbers. On the other hand, the principal provisions of IES CS-8 can be extended to these devices as long as the leaktightness, workmanship, resistance, and test requirements of IES CS-8 can be met. (IES CS-8 was written so that its governing requirements could be extended to designs other than type I and type II cells.) As with cells, all surfaces of PSU adsorbers in contact with the adsorbent are stainless steel. The outer walls of the unit are part of the pressure

boundary of the housing in which it is installed (see Fig. 3.11). The beds, which are usually but not always deep beds (i.e., 4 in. or more), are either inclined, as shown in Fig. 3.11a, or vertical to permit gravity flow of adsorbent to the extraction port. Packing density of the adsorbent is not as critical as in unit cells that are subject to vibration and shock during transport and handling, because any settling can be accommodated by "topping off" the unit with additional adsorbent. Emptying of the PSU adsorbers is generally by vacuum or by air fluidization plus aspiration. At least one design employs gravity emptying by opening the bottom of the beds to a hopper beneath the unit. When PSU adsorbers are

used with iodized carbon adsorbents, an important design consideration is the capability to positively extract the carbon if it gets wet. Many adsorber installations include the provision of water sprays to suppress carbon fires. If these sprays are activated, the mass of carbon can become a difficult-to-air-transport slurry, similar to wet sand. Extraction of wet iodized carbon from a PSU adsorber is essential within 24 hr of the wetting, because corrosion is possible if it is left in contact with the stainless steel of the beds and pressure boundary.

An adsorber design used in earlier systems was the multiple-tray CBR (chemical-biological-radiological) filter unit shown in Fig. 3.13. Because of the caulked-joint construction and the inability to replace adsorbent except by replacing the entire unit, their use in nuclear applications is not recommended. Cylindrical adsorbers (Fig. 3.14) and gas mask canisters are sometimes used in small installations such as glove boxes, machine-tool hoods, and small-volume reactor and radiochemical plant off-gas systems. However, they find no application in large adsorber systems.

3.4.4 Adsorbents

Detailed requirements for nuclear-grade gas phase adsorbents are specified in RDT M 16-1.[28] The requirements are of two general types: (1) the efficiency and desorption tests discussed in Sect. 3.4.2 and (2) physical properties that characterize the product that has been subjected to performance tests.

Coconut is the most widely used activated-carbon base material at this time. However, an increasing
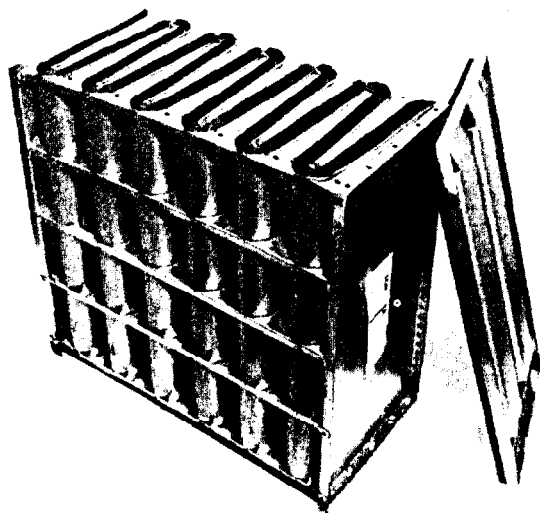

Fig. 3.12 Pleated bed (IES CS-8, type 1) adsorber cell. This design is obsolete. Weighs approximately 160 lb. Courtesy Barnebey-Cheney Co.
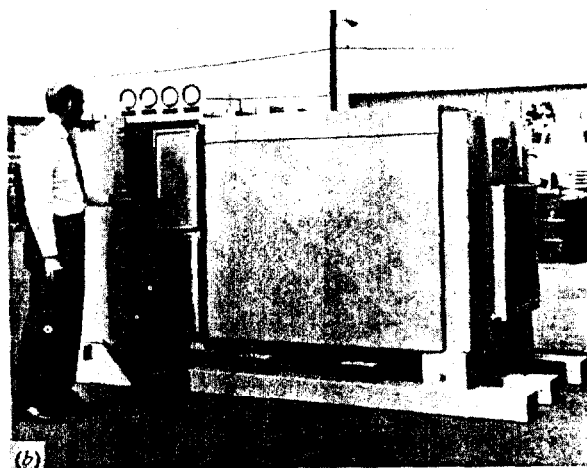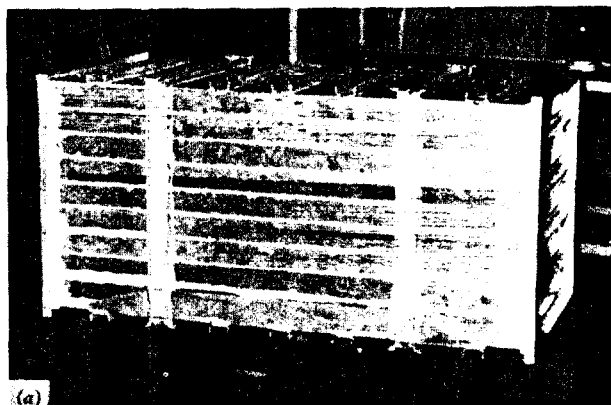

Fig. 3.13. Multiple-tray adsorber for CBR filter unit. Not recommended for nuclear applications. (a) Adsorber tray section. Note joints between trays. (b) CBR filter unit. Courtesy Farr Co.
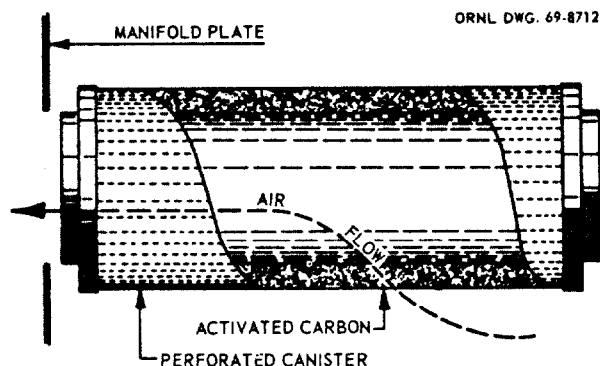
61

Fig. 3.14. Canister-type adsorber cell. These may be installed individually or in an array of 16 canisters gasketed into a plate with arrangement for installation of the assembly in a manner similar to that for pleated bed cells.

worldwide demand for coconut carbon has caused significant price increases, has decreased its availability, and has accentuated the need to find alternative base materials. Recent studies indicate that coal-base carbons can be impregnated to trap and retain radioactive iodine and organic iodine compounds as effectively as coconut, and these carbons may be used increasingly in the future.[30] The studies included a survey of all domestically available activated-carbon base material, plus tests to evaluate properties of major interest.[47]

Certain physical properties are important to the user. *Hardness*—attrition and crushing of carbon granules under service conditions can result in dusting and subsequent escape of contaminated carbon, or in channeling through the bed with subsequent leakage of contaminated air or gas from the adsorber. Very hard carbons are desirable to resist fracture, abrasion, and crushing; a minimum hardness of 92% is recommended. Hardness is currently determined by the ball-pan (or Ro-tap) method given in RDT M 16-1. To minimize service degradation, vibration and pulsation in the air handling system must be minimized, and adsorber units should be installed with beds horizontal so that there is a minimum pressure head on the carbon granules. *Carbon tetrachloride activity* is difficult to relate directly to performance but to some extent is a measure of surface area and a direct measure of the degree of activation; it is, therefore, an indicator of the uniformity of product. The test is made routinely (before and after impregnation) by the manufacturer for quality assurance (QA) purposes, and test results should be specified as one of the items of data to be furnished. Minimum values that conform to the test

results obtained on the qualified lot of product should be specified. *Apparent density*—carbon must be packed into beds so that settling does not occur during shipping, handling, installation, or operation. Packing density should approach the apparent density as determined at the time of qualification. *Mesh size* of the carbon is limited by the availability of perforated-steel retaining screens. Although some adsorber designs employ cotton fabric screen liners (scrims) to retain the carbon, thus permitting the use of very fine (12- by 30-mesh)[46] carbon, the practice is not recommended for nuclear exhaust applications, because the scrim could burn or deteriorate and cause the release of fines. There is also some possibility that the cotton might contribute to converting elemental iodine to an organic compound, which would increase the loading on the impregnant. For stiffness, the screens should be made from a steel sheet as heavy as possible, and the holes should be as small as possible to retain the smallest possible carbon granules. The open area of the screens should be as great as possible to minimize airflow resistance. At present, 220 holes (0.045 in. in diameter) per square inch (open area = 35%) is the limit of the steel perforator's capability in No. 26 U.S. gage stainless steel and No. 24 U.S. gage carbon steel. This limits minimum carbon size to No. 16 U.S. mesh.[46]

3.4.5 Inorganic Adsorbents

Inorganic adsorbents are of interest in many nuclear applications because they are noncombustible and therefore eliminate one of the potential hazards of activated carbon. The major inorganic adsorbent of current interest is silver-exchanged zeolite. Silver oxide and silver nitrate impregnated alumina have been investigated in the laboratory and show some promise. Although retention of methyl iodide by alumina decreased strongly with increasing humidity and airflow, it increased substantially at higher temperatures.[48] Impregnated aluminum silicate has been made available by one manufacturer but to date has not been used under service conditions. Silver zeolite (AgX), on the other hand, looks promising in both laboratory testing and field use. Its advantages and characteristics include (1) nonflammability and high-temperature iodine retention (samples containing adsorbed radioiodine have been heated to temperatures as high as 900°C before measurable amounts of radioiodine were released); (2) high-temperature operation (efficiency increases with temperature, and efficient methyl iodide adsorption is still achievable at temperatures

as high as 400°C); (3) low explosion hazard when used in air streams containing high concentrations of nitrogen oxides; (4) high efficiency under service conditions that are unfavorable to activated carbon, including high (>250° F, or 120°C) air temperatures and relative humidities of 90 to 95%; (5) adsorbed iodine compounds form solid, insoluble products with silver zeolite, which is desirable from the standpoint of waste management;[49] and (6) high MPL_d (85 mg I/g AgX is claimed,[50] although an MPL_d no greater than 45 is recommended for design purposes). Offsetting these advantages of silver zeolite are its very high cost (it may cost 40 to 50 times more per cubic foot of bed volume than comparable activated carbon) and its lower efficiency at lower (e.g., room) temperatures. For certain operations, particularly for fuel processing plant secondary treatment systems where high temperature and high concentrations of nitrogen oxides may be the rule, silver zeolite may provide an acceptable choice even at the higher cost. There is some indication, however, that service life may not be as good as claimed. In one experimental facility off-gas system, the efficiency of a silver zeolite adsorption system dropped from over 99.9% to about 91% in approximately 18 months. Although silver zeolites are not supposed to be as subject to poisoning by "tramp" contaminants in the environment as activated carbon, poisoning apparently occurred in this case. No formal explanation for the decrease has been proposed. In the case of an experimental fuel reprocessing development facility, hydrogen chloride vapors were inadvertently introduced into the air stream leading to silver zeolite adsorbers, thereby causing nearly instant incapacitation.

In Germany an inorganic silver nitrate-impregnated catalyst carrier, built of amorphous silicic acid with small additions of aluminum oxide, has been used with good success.[51] The material is inexpensive and uses relatively low silver loadings, as compared with silver zeolite, and gives high removal efficiencies for radioactive iodine and methyl iodide at relative humidities on the order of 70%. Efficiencies at 95 to 100% RH were poor, however. The price is reported to be about three times that of equivalent activated carbon but only $^1/_{10}$ that of silver zeolite.[51]

3.4.6 Adsorption System Design

System properties of primary concern are (1) efficiency, (2) MPL of the adsorbent, (3) airflow capacity, and (4) airflow resistance. By assuming that an adequate adsorbent is selected, that the required

gas residence time is maintained, that no poisoning or excessive aging has occurred, and that no leaks in the system have developed, system efficiency should be equivalent to the efficiency of the adsorbent, as determined by laboratory testing of samples taken from the system.

Maximum permissible loading determines the minimum quantity of adsorbent required in the system and is a function of (1) the adsorbent's capability to trap, and retain, radioiodine (or other adsorbates of interest) and (2) the quantity of adsorbent required to disperse trapped fission products so that carbon ignition becomes unlikely (i.e., MPL_d for desorption vs MPL_i for ignition). The MPL_d required to prevent breakthrough under normal operating conditions varies with the radioiodine form (elemental or organic) and differs for different adsorbents. There is substantial disagreement as to the design value for MPL_d for each of the radioiodine forms, and currently there are insufficient data on which to base any hard numbers. MPL_d's as low as 2 mg total I/mg C, to as high as 50 mg I_2 and 5 mg CH_3I/mg C have been proposed for continuously on-line and normally off-line systems respectively. All of these values are high when desorption of iodine or ignition of carbon due to fission product heating under accident conditions is considered.

The concentration of iodine in the air that flows to the adsorption system of a reactor in the unlikely event of a major accident may range from a few parts per million to as high as 500 ppm, depending on reactor size, degree of fuel burnup at the time of the accident, and the nature of the accident. Some general assumptions in a DBA are that 50% of the fuel inventory will be released to the containment; 50% of the amount released (i.e., 25% of the fuel inventory) will plate out on the walls and floor of the containment; and the iodine that reaches the adsorbers will be distributed as particulates, organic iodides, and elemental iodine in the proportions 5, 4, and 91.[52] However, any particulate iodine will be collected on the demisters or HEPA filters upstream of the adsorbers and may desorb and subsequently collect in the adsorbers. Also, as much as 10% of the elemental iodine collected in the adsorber beds of an activated carbon system may convert to penetrating forms of iodine, primarily organic iodides, in the presence of moisture and a high radiation field.[53] For system design purposes, therefore, a distribution of 85 parts elemental iodine and 15 parts organic iodides, with zero particulates, is recommended. A substantial portion of this iodine (the exact propor-

tion will depend on the degree of fuel burnup) will exist in the form of heat-generating radioiodine and will contribute to fission product decay heating of the carbon, which, if adequate cooling airflow is not maintained, may cause desorption of trapped iodine or ignition of carbon in the beds. Of these two possibilities, desorption of iodine is the more serious for two reasons: first because it would constitute a loss of containment for radioiodine, and secondly because bed temperatures will never reach the ignition point if sufficient airflow to prevent desorption of trapped iodine is maintained. Sufficient airflow is necessary to keep bed temperatures below 230°F, probably on the order of 6 to 10 fpm. An MPL of 2.5 mg total iodine (including inert and radioactive isotopes as both elemental iodine and organic compounds) per gram of carbon is considered adequate to prevent significant fission product decay heating provided a minimum airflow of 6 to 10 fpm under accident conditions is maintained.[53]

To determine the minimum quantity of carbon required in a specific system, the quantity of inert and radioactive iodine that may be trapped in the adsorbers must be estimated. Using the MPL of 2.5 mg total I/mg C and the assumptions on iodine distribution noted previously, the minimum quantity of carbon in the system can be estimated from the equation

$$C = 0.22 \, Q \, , \tag{3.1}$$

where

C = minimum quantity of carbon required, lb;

Q = potential iodine inventory that could be released, g.

Using this equation, a 1000-MW(e) reactor with a potential iodine inventory of 15,000 g would require a minimum of 3300 lb of carbon to provide adequate protection against desorption and ignition under accident conditions. This amount is more than adequate to meet the requirements for efficiency and retention under normal conditions.

System airflow is a function of the quantity of carbon in the system and of gas residence time. Although the minimum gas residence time of 0.20 sec is required for effective sorption of organic radioiodine compounds, a minimum of 0.25 sec is recommended for design purposes. This provides the conservatism necessary to account for adsorbent bed thinning due to the nearly unavoidable warpage and

camber of screens used to hold the adsorbent in modular cell and PSU adsorbers. Gas residence time can be increased by increasing bed depth or, for a fixed bed depth, by decreasing airflow velocity (i.e., by underrating). Increasing bed depth over the 2-in. minimum employed in both PSU and modular cell adsorber designs and recommended in Regulatory Guide 1.52[33] has the advantage of increasing system reliability by increasing holding capacity. It has the disadvantages of higher cost and, in activated carbon systems, of slightly decreasing ignition temperature.[43] Ignition temperature also decreases with aging of the carbon, particularly in continuously on-line systems. Minimum operational airflow capacity can be determined from the equation

$$C = \frac{Ntn(A-b)}{28.8 \, ST} \, , \tag{3.2}$$

where

C = minimum system design airflow, cfm;

N = number of cells or adsorber assemblies in the bank ($N = 1$ for a PSU);

n = number of beds per adsorber assembly ($n = 2$ for IES CS-8 type II cells);

t = bed thickness, in.($t = 2$ for IES CS-8 type II cells);

A = total area of all bed screens of one cell or of a PSU, in.^{2};

b = total unperforated area of screens having total area A, in.^{2};

S = number of screens per cell or PSU adsorber;

T = minimum gas residence time required for effective sorption, sec.

For IES CS-8 type II cells and gas residence time of 0.25 sec, Eq. (3.2) reduces to

$$C_{11} = 333 \, N \, . \tag{3.3}$$

For an installation of modular cell adsorbers, gas residence time can also be increased by providing two banks in series. This not only increases holding capacity and system reliability but avoids the decrease in carbon ignition temperature (since each bed is only 2 in. thick) and provides series redundancy. Because the first bank serves as a guard bed, most of the aging, weathering, and poisoning of the adsorbent would take place in the first bank, and service life of the second bank should be greatly extended. All these advantages are gained at increased investment costs, building space charge (because of the greater space required), and operation costs (because of the greater power requirements

necessary to accommodate the increased system resistance).

With respect to fission product decay heating, different isotopes of iodine have different heat-producing potentials and different decay rates. For continuously on-line systems in vented containment (see Sect. 9.8) and in-containment postaccident air cleanup systems, transport of radioiodine is rapid (from a few minutes to as long as 30 min, depending on the length of the transport path) and all heat-producing isotopes must be considered in estimating the heat production potential in the adsorber system. In double containment systems the fission product transport time is much greater, thus permitting the short life heat-generating isotopes to decay to the point that their contribution to the heat-producing potential (in the adsorbers) is negligible.[54] In these systems it is likely that only the contribution of I-131 (half-life of about 8 days) need be considered. In either case, the equilibrium inventories (in the fuel) of the isotopes of concern should be used for estimating the heat-generating potential in the carbon of the adsorbers.

Airflow resistance is a function of bed depth, adsorbent mesh size, and airflow velocity. The resistance of a bank of IES CS-8 type II cells, having 2-in.-thick beds filled with 8- by 16-mesh carbon and operated at a volumetric airflow rate of 333 cfm (40 lin fpm superficial velocity) is 1.1 in.wg. With HEPA filters upstream, resistance does not increase with time under service conditions.

3.5 DEMISTERS

3.5.1 Introduction

Demisters (also termed entrainment separators, mist eliminators, or moisture separators) are required in some nuclear air cleaning systems to protect the primary components (HEPA filters and adsorbers), from damage or loss of function due to entrained moisture. HEPA filters are highly efficient collectors of solid and liquid particulate matter. Because they can plug rapidly when exposed to high concentrations of liquid, the result can be decreased airflow, increased pressure drop, and perhaps rupture of the filter pack. In adsorbers, water deposition may increase pressure drop (by filling interstitial spaces between granules of adsorbent) and decrease efficiency and capacity.

Sensible moisture may stem from various sources depending on the system. In radiochemical, fuel processing, and some laboratory operations, droplets generated in scrubbers or chemical operations may be released to the airstream; or saturated gas streams, upon cooling, may produce droplets by condensation. In a water-cooled and/or water-moderated reactor, in the very unlikely event of a loss of coolant accident (LOCA), large volumes of steam will form which, upon condensation in the containment air, will pass to the postaccident air cleanup system filters and adsorbers. If sprays are provided to reduce post-LOCA pressure in the containment space of the reactor, entrained water droplets from these could also be present in the air flowing through the filters. In plants that have fire protection sprinklers in the space served by the air cleaning system, or in the duct leading to the air cleaning system, activation of the sprinklers would produce sufficient sensible moisture to adversely affect the filters in some instances. In any situation where free moisture may be present either under normal or upset conditions, a stage of demisters should be provided upstream of the filters.

With condensing steam, most of the entrained water droplets will be in the size range of 1 to 20 μm. With sprays and sprinklers, the steam will exist as droplets ranging from submicron diameters to 2000 μm in diameter or larger.[55] Most of the droplets generated by sprays or sprinklers will be large (mass median diameter, MMD, will approach the diameters of the larger drops) and can be effectively removed by wave plates or other coarse moisture separators. However, after removal of these droplets, there may be a sufficient mass of water among the smaller drops remaining to cause plugging of unprotected HEPA filters. Droplets in the range of 1 to 20 μm in diameter pose the greatest threat to HEPA filters, because droplets larger than this range are readily removed, and the mass of free water represented in droplets smaller than 1 μm is too little to pose a likelihood of plugging. Within the 1-to-20-μm range, however, free water cannot be removed by inertial separation alone, and use of more effective and higher pressure-drop devices is required. Filter plugging is a time-concentration phenomenon; that is, although sustained exposure to low concentrations of entrained moisture (as might exist on a seacoast or due to condensation of water vapor above a pool or wetted surface) may eventually cause plugging if the air remains saturated, such an occurrence is unlikely. However, short-term, even minutes, exposure to high concentrations of entrained water, as might exist from a spray or condensation from a broken steam line, may cause rapid plugging. In tests of plugging of HEPA filters

65

by water spray,[56] the airflow through a 1000-cfm filter, after being subjected to a water spray flow of 0.38 gpm per 1000 cfm of airflow, dropped to and leveled off at 630 cfm in about 20 min. With a water flow of 0.95 gpm per 1000 cfm, airflow dropped to about 300 cfm in 16 min, and if the test had been continued, total plugging would probably have occurred within an hour because of the inability of the filter to drain collected water. In a test with very coarse spray (MMD <2000 μm) at a delivery rate of 6.5 gpm per 1000 cfm airflow, nearly complete plugging (90% decrease in airflow) occurred in approximately 6 min, and spray droplets punched holes in the filter medium. In another test,[57] exposure of unprotected HEPA filters to wet steam and air resulted in nearly complete plugging in less than 6 min. However, those HEPA filters protected by an adequate demister (capable of removing 1- to 5-μm-diam water droplets at an efficiency of >99%, and coarse droplets at an efficiency of 100% at a water loading rate of 8 gpm) were still serviceable, with no observable decrease in efficiency. The serviceability determination was made after 10 days exposure to air containing a visible water fog, preceded by exposure to wet steam and airflow for 30 sec at a flow rate of 10,000 cfm through the 1000-cfm demister–HEPA filter combination. Both series of tests indicated that dust collected on the HEPA filter decreases its water repellency and increases its water retention.

It can be concluded that, although the HEPA filter can drain some quantity of collected water and therefore accept some degree of water loading without plugging, there is a threshold time-concentration value above which demisters must be provided. For clean filters, this time-concentration value appears to be such that the water retained in the filter will be less than 2 lb per 1000-cfm airflow capacity under equilibrium conditions (i.e., water flow rate of about 0.35 gpm per 1000 cfm of airflow). However, such a value must be used with caution because of the increase in water retention with increasing dust loading or aging of the filter, and a time-concentration value that will produce a maximum retained water loading of 1 lb of water under equilibrium conditions should be observed as a practical consideration (maximum water delivery rate of about 0.18 gpm per 1000 cfm of airflow). Sustained wetting gradually decreases the tensile strength of HEPA filter media, and intentional operation under such conditions is not recommended. Radiation also decreases the water repellency of HEPA filter media.[58]

3.5.2 Demisters for Reactor Applications

The Nuclear Regulatory Commission recommends that demisters be provided in reactor postaccident cleanup systems and in other ESF systems in which potential water or steam release may occur.[59] Furthermore, it recommends that the demister be of nonflammable construction and that its design be qualified by a prototype test. Acceptable qualification procedures are described in USAEC Reports DP-812 and MSAR 71-45.[57,60] Such tests should demonstrate that the demister is

1. At least 99.9% efficient, on an arrestance (i.e., weight percent) basis, for entrained water and condensed steam in the droplet range of 1 μm to 2000 μm in diameter, at duct velocity from 250 to 2500 lin fpm, and water delivery rate of 8 gpm per 1000 cfm of installed HEPA filter capacity.

2. At least 99% efficient, on a count basis, for droplets in the range of 1 μm to 10 μm in diameter, at duct velocity from 250 to 2500 lin fpm.

3. Nonflooding and nonreentraining at a water–steam delivery rate of 8 gpm at duct velocity of 2500 lin fpm.

4. Capable of withstanding temperatures of up to 160°C and gamma radiation exposure up to 10^6 rads integrated dose without visible deterioration or embrittlement of the materials of construction.

Wire mesh demisters used in chemical processing and panel-type entrainment used in air conditioners and air washers are inefficient in the 1-to-10-μm droplet range; and the highly compressed packed-fiber mist separators used for fume control in chemical plants, which are efficient in this droplet size range, have too high a resistance and too low a flooding capacity at the high air–water flow rates required for reactor postaccident air cleanup service. Wave- or bent-plate moisture separators (Fig. 3.15) are strictly impingement-type devices and are effective only against large (>100 μm) drops. However, they can be useful as pre-separators to protect a more efficient demister downstream from high concentrations of large drops, similar to the application of a prefilter before a HEPA filter. Tests showed that commonly available panel filters and wire mesh demisters are useless in removing entrained water droplets in the 1-to-20-μ-diam range, and one
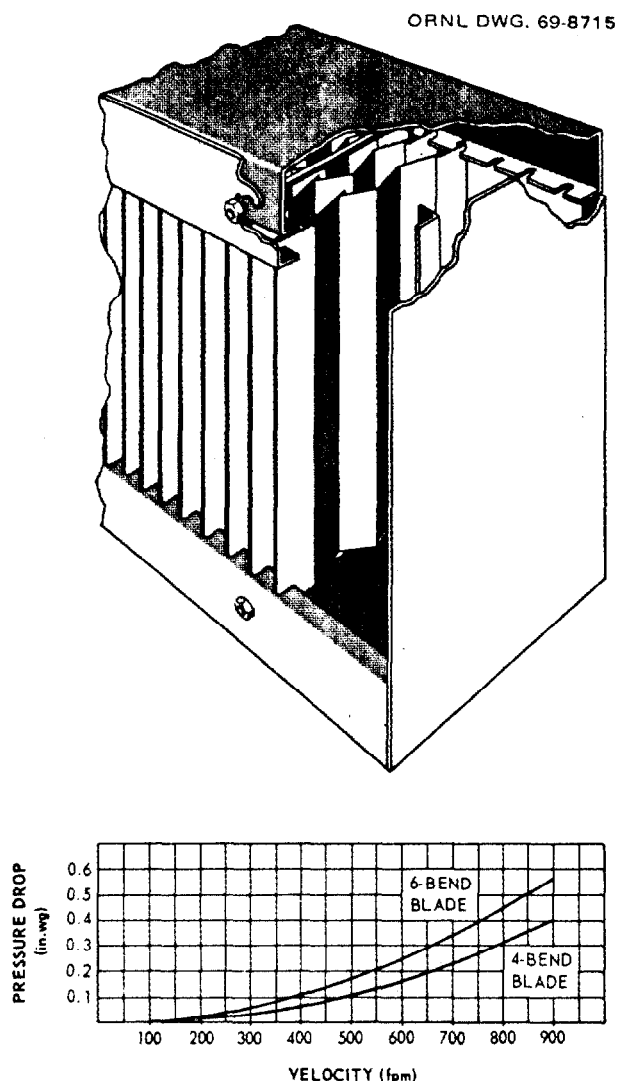
ORNL DWG. 69-8715

Fig. 3.15. Wave-plate separator—typical configuration and pressure-drop characteristics.

fiberglass panel filter was blown out of its retainer after only 10 sec of exposure to wet steam.[57]

As of February 1976, four commercially available demister designs have been qualified for nuclear reactor service. Two of these demisters are similar and consist of an assembly of alternating coalescing and draining mats in a stainless steel case, 24 × 24 × 5 to 5½ in. thick. The coalescing layers are knitted from fine multifilament fiberglass yarn (having individual filaments of less than 20 μm in diameter) on a stainless steel wire matrix. The drain layers are crimped and knitted stainless steel mesh (0.011-in.-diam wire). Screens on each face prevent blowout at high pressure drop, as might occur during the first few seconds of a reactor DBA. The demister weighs

about 30 lb; has a rated airflow capacity of 1600 scfm at 0.90 in.wg pressure drop when dry; and water removal rates of 650 lb/hr for drops 100 μm and larger, 480 lb/hr for drops in the 10 to 70 μm range, and 2.5 lb/hr for drops 10 μm and smaller. Qualification of the unit shown on the left in Fig. 3.16 was reported in MSAR-71-45.[60] The unit shown on the right in Fig. 3.16, available from ACS Industries, was qualified by the Harvard Air Cleaning Laboratory by using a similar procedure.[61]

Another demister design, made by American Air Filter and shown in Fig. 3.17, consists of a wave-plate separator followed by three 2-in.-thick nonwoven fiberglass mats. The mats are installed in cells as shown in Fig. 3.18 and the grid assemblies, made from ⅛-in.-diam stainless steel wire, prevent blowout of the mats at high overpressure (2 to 3 psi). The production model of this unit is 24 × 24 × 24 in.; weighs 111 lb; has a pressure drop of 0.78 in.wg at rated airflow when dry; and has water removal rates of 440 lb/hr for 100-μm-diam drops, 310 lb/hr for 10- to 70-μm-diam drops, and 6.4 lb/hr for drops smaller than 10 μm in diameter.[60,62]

The fourth demister, available from the Otto H. York Company and used in the reactor confinement systems at Savannah River Laboratory, is a multilayer mat knitted from fine (approximately 20-μm-diam) Teflon[63] filament on a stainless steel wire matrix. The unit shown in Fig. 3.19 is 24 × 24 × 2 in. thick and has a stainless steel case and ⅛-in.-diam stainless steel reinforcing wires on each face. Qualification of this unit was described in USAEC Report DP-812.[57] Objection to fluorocarbon (TFE) plastic fiber, such as Teflon, has been raised in some quarters because of its claimed unsatisfactory radiation resistance. Demisters of this design were tested at a dose rate of 6 × 10⁶ rads/hr for 100 hr and, although they became embrittled and would have broken if subjected to mechanical shock, they were still able to maintain their function. This dose is considered much higher than any that would be encountered in the demisters under any conceivable accident conditions, because most of the activity released under accident conditions would be in gaseous form that would pass right through the demisters, to be captured in the adsorbers downstream.[64]

3.5.3 Performance

The performance of demisters, like that of particulate filters, is defined in terms of removal efficiency for a specific particle (droplet) range, airflow
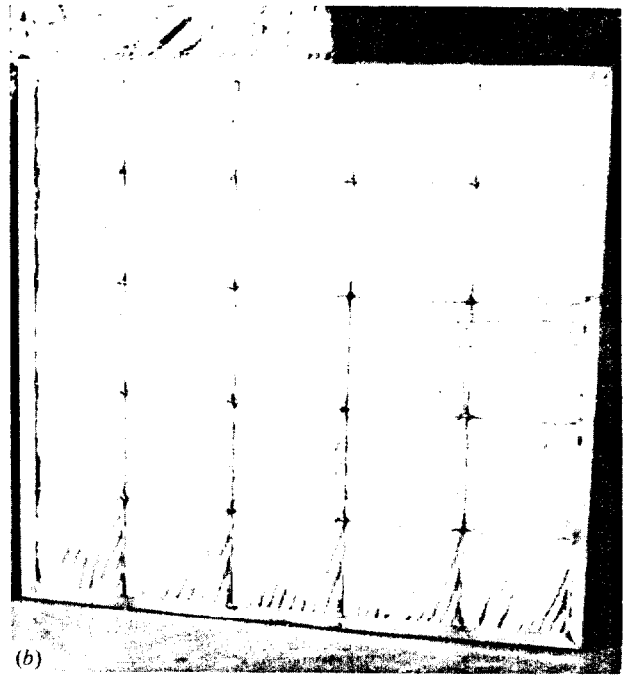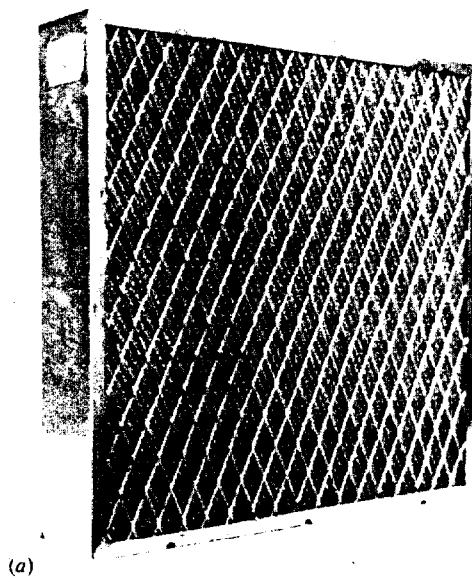
Fig. 3.16. High-efficiency demisters for nuclear service. (a) Courtesy Mine Safety Appliances Co.; (b) courtesy ACS Industries.

25,000-cfm SEPARATOR UNIT

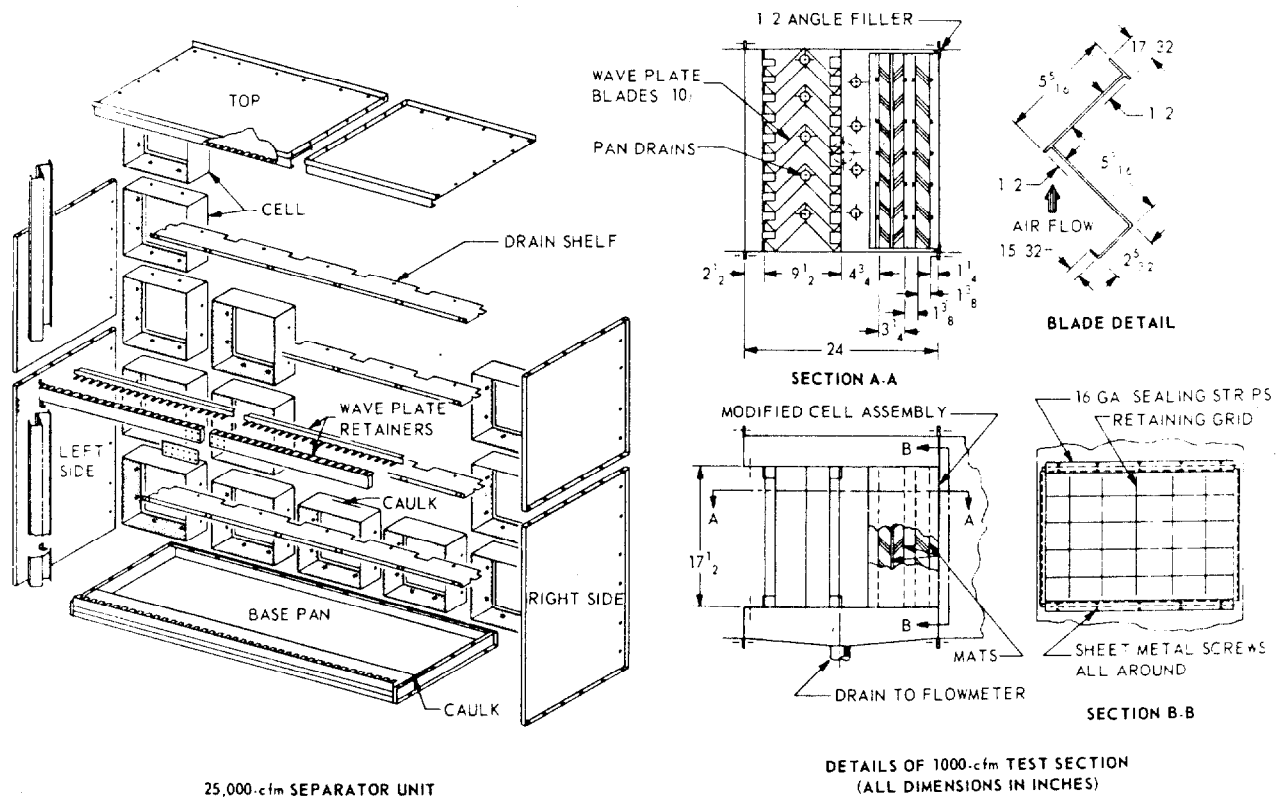DETAILS OF 1000-cfm TEST SECTION
(ALL DIMENSIONS IN INCHES)

Fig. 3.17. Exploded view and details of demister qualified for reactor postaccident air cleanup service. Courtesy American Air Filter Co.
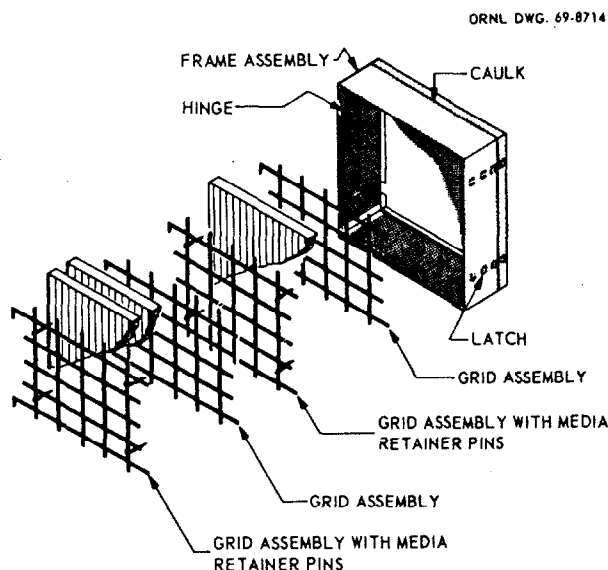
Fig. 3.18. Exploded view of typical cell assembly for demister shown in Fig. 3.17.
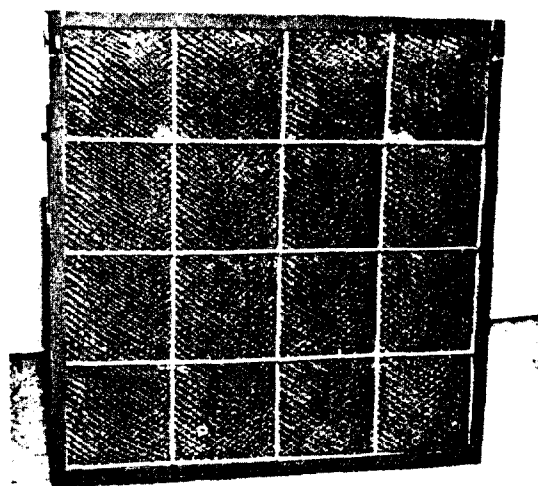

Fig. 3.19. Knitted Teflon and stainless steel wire demister used in Savannah River reactors, made by Otto H. York Co. Courtesy E. I. du Pont, Savannah River Laboratory.

capacity, and resistance to airflow. The forces acting on liquid droplets in an air stream are identical to those acting on solid particles and the same filtration mechanisms (diffusion, impaction, and inertia) apply for both situations. In nuclear reactors, demisters must remove 99% of all droplets down to about 1 μm in diameter at airflow rates of several thousand cubic feet per minute per demister, and at water delivery rates of up to 1 gal (8.4 lb) per 1000 cfm of steam-air mixture.

Wave-Plate (Bent-Plate) Demisters. Just as it is desirable to protect HEPA filters from high concentrations of coarse particles, it is also desirable to protect knitted or nonwoven-mat demisters from high concentrations of large water drops (50 to 1000 μm in diameter or larger). Because it takes more power to remove small drops (because of the higher resistance of the units capable of removing small drops) and because large quantities of water may unduly increase the water load and airflow resistance, it is uneconomical to use knitted fabric or nonwoven fiber filters to remove the large drops produced by reactor postaccident cooling sprays. Large drops are effectively removed by wave-plate demisters of the type shown in Fig. 3.15. Their efficiency is practically 100% for drops over 400 μm but decreases to 60%, or less, depending on blade geometry, for droplets in the range of 10 to 50 μm.[65] Wave-plate demisters can handle very large volumes of air at high velocity (as high as 1500 fpm for some types) with low pressure drop (Fig. 3.15). Because efficiency is dependent on impaction and inertial effects, operation at less than about 400 fpm is not recommended. With most types, water carry-over may occur at velocities higher than 700 fpm.[55]

Knitted Fabric and Nonwoven Fiber Mat Demisters. Knitted fabric and nonwoven fiber demisters of the types shown in Figs. 3.16, 3.17, and 3.19 are the most satisfactory devices for removing small and intermediate-sized droplets (1 to 100 μm). Their design is a compromise between airflow capacity, resistance, size (i.e., materials cost), and service life. Recommendations of the manufacturer should be followed closely when supported by test data. Because drop removal is effected mainly by impingement, removal efficiency improves with increasing flow velocity and decreasing fiber diameter. The maximum fiber diameter for effective removal of droplets in the 1-to-10-μm range is about 20μm.[66] If a demister is comprised of a series of incremental layers, the droplet removal efficiency of the complete demister is the sum of the efficiencies of the individual layers. Although efficiency can be increased by increasing the thickness of the separator, this would increase the pressure drop and, therefore, operating costs; and there is a practical limit to increases in efficiency that can be attained at a given velocity. Overall efficiency can be increased to some extent by increasing the velocity, but this is at the expense of higher pressure drop and operating costs, and it also decreases efficiency for smaller droplets. Within limits, the higher the velocity, the thinner the demister (i.e., the fewer the layers) required for a

given efficiency and the less the material required, which, in turn, results in lower procurement costs.[66]

For a given construction (fiber diameter and packing density), the airflow resistance of a demister at constant velocity increases directly with the number of identical layers. Therefore, there is a point of diminishing returns at which the cost of increasing the efficiency is offset by increased operating and materials costs. Efficiency can also be increased by increasing the packing density. However, airflow resistance increases even more rapidly than the improvement in efficiency. For this reason, the very efficient packed-fiber mist eliminators (Fig. 3.20) that have gained wide acceptance in the chemical industry are not recommended for nuclear reactor postaccident cleanup systems. Table 3.12 gives approximate operating velocities of the demisters discussed in this section. Knitted and crimped-wire separators are more efficient when installed vertically (i.e., horizontal airflow) than horizontally (as in most vessel off-gas and scrubber installations).[67]

Because mat-type demisters are relatively efficient particle filters, they must be cleaned or replaced periodically if installed in continuously on-line systems. The knitted-fabric demister shown in Fig. 3.19 can be steam cleaned; the nonwoven fiber mats shown in Fig. 3.17 must be replaced. The pressure drop at which cleaning or replacement must take place is based on the capacity of the system fan. Manufacturer's recommendations on overpressure capability should be followed closely, and units should be cleaned or replaced soon enough so that an adequate margin of safety is allowed for the potential increase in pressure that would result from water loading.

The demister and its operating conditions must be tailored for each situation, and performance tests must be made under simulated conditions to obtain the optimum design of separator and system.

3.5.4 Normal Off-Gas Demisters for Radiochemical Service

Mist eliminators are often required in scrubber and radiochemical-operation off-gas systems to protect downstream filters from moisture and from acid or caustic fumes. Two types have given satisfactory service in radiochemical plant service.

Packed-Fiber Mist Eliminators. Packed-fiber mist eliminators of the type shown in Fig. 3.20 have given excellent performance for acid fumes in industrial

service and can be tailored, by selection of fibers and materials of construction, to a wide variety of applications.

The cylindrical element shown in Fig. 3.20a consists of a densely packed fiber bed, rigidly held between heavy corrosion-resistant screens. The unit shown is 24 in. in diameter and 120 in. long with a mounting flange for suspension from a support plate. Gas flows from the outside to the inside hollow core from which the clean gas exits at the top and the collected liquid exits at the sealed bottom through a drain pipe. Alternate designs with gas flow from the inside to the outside are also available. Fibers and other materials of construction are selected for their resistance to the reagents present in the off-gas. Operating velocities for this type of unit range from 5 to 50 lin fpm through the media, depending on design and performance requirements. Figure 3.20 shows the operating characteristics of two designs. Designs with collection efficiencies for submicron particles up to 99.98 wt % have been demonstrated on large-scale industrial processes.[68,69] The mechanisms of mist separation for this type of element are diffusion, impaction, and inertial effects, with diffusion controlling for submicron particles.

In one radiochemical operation, cylindrical elements with 3-in.-thick beds of 20-μm fibers and fiber-packing density of 11.5 lb/ft^3, operating at a gas velocity of 15 fpm through the bed, gave 99.99 wt % efficiency for droplets 3 μm and larger and 99.3 wt % for droplets in the 0.3-to-0.5-μm range.[70] The pressure drop of this demister was 4 in.wg when clean and was approximately 10 in.wg after a year of operation when the elements were wet and a considerable amount of solids had been collected. The maximum temperature was 200° F and the measured efficiency for Cs-137 was over 96 wt %.

High-velocity packed-fiber mist eliminators (250 to 500 lin fpm through the media) have found

Table 3.12. Economic operating velocities for demisters

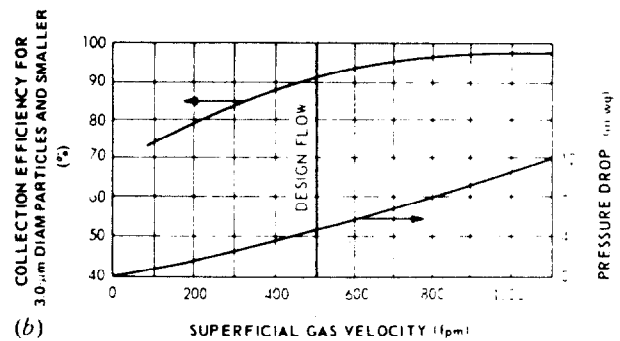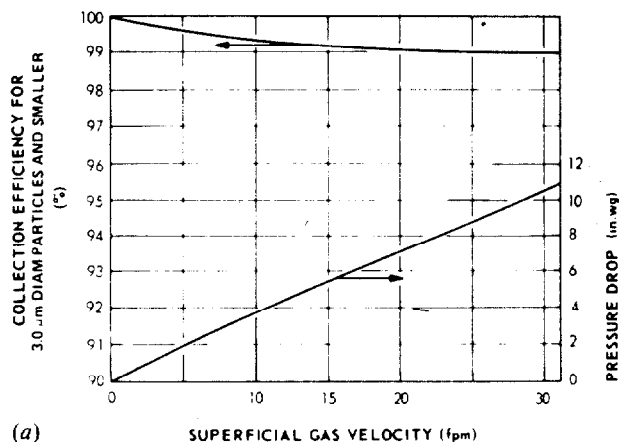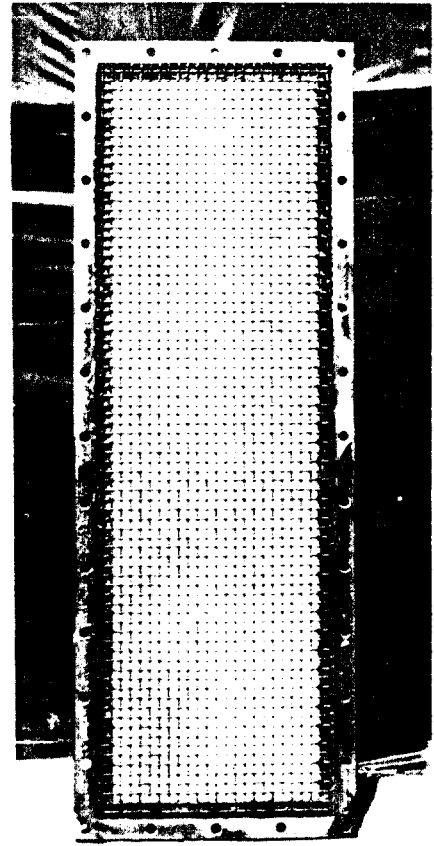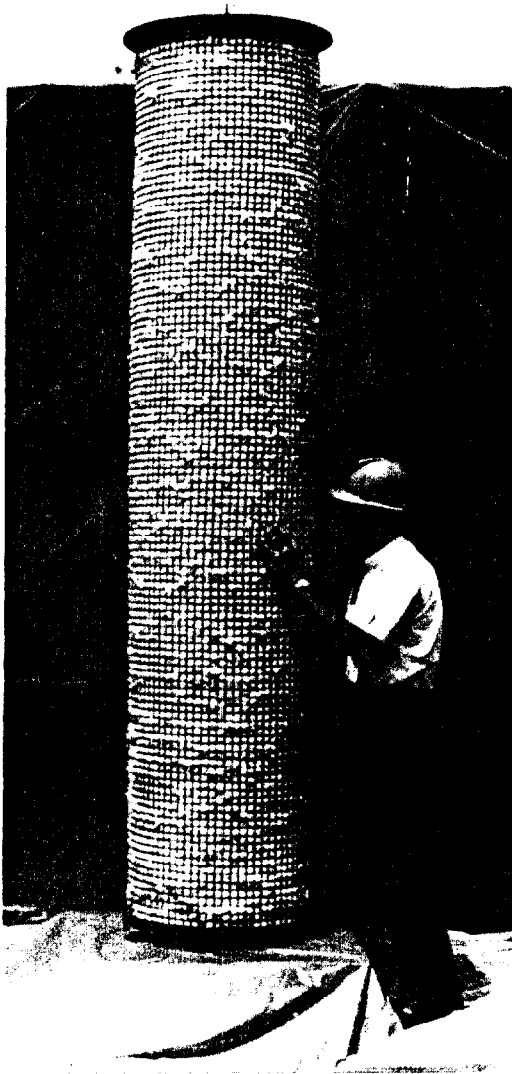| Type, thickness	Airflow	Velocity (fpm)
Knitted fabric, 2 in.	Horizontal	420–480
	Vertical	280–320
Knitted fabric, 4 in.	Horizontal	270–300
	Vertical	220–260
Nonwoven fiber, 6 in.	Horizontal	240–280
6-bend wave plate	Horizontal	550–650
Wire mesh, 4 in.	Horizontal	720–840

Fig. 3.20. Brink packed-fiber mist eliminators and operating characteristics. (a) High-efficiency element, (b) high-velocity element. Courtesy The Monsanto Co.

extensive application in the chemical industry.[71] The rectangular element shown in Fig. 3.20b has overall dimensions of $18\frac{1}{2}$ in. by 53 in. and utilizes impaction as the controlling collection mechanism. Collection efficiencies of essentially 100 wt % are achieved for particles over 3 μm in diameter with lower efficiencies for smaller particles. Elements similar in appearance to the high-velocity model have also been developed which have a pressure drop of 1 in.wg or less. This type, known as a "spray catcher," has essentially 100 wt % efficiency on particles greater than 5 μm in diameter but low efficiency on smaller particles.

Packed-fiber mist eliminators are efficient solid-particle collectors but can be clogged by high dust loadings. They are sometimes made self-cleaning by adding atomized water to a gas stream containing acid or caustic fumes; under other circumstances they may have to be cleaned with steam or by backwashing. The units are particularly subject to clogging when operated completely dry, especially if viscous dusts or lint is present. In low dust concentrations this type of unit has operated for years without cleaning, which indicates the desirability of efficient building supply-air cleaning. In radioactive applications the arrangement of two units in parallel is desirable so that flow can be switched back and forth for maintenance or in the event of emergency without shutting down the system. Because water that collects on the fibers can seep through the bed, particulate carry-over is possible, as discussed in Sect. 3.5.1.

Perforated-Plate Mist Eliminators. The perforated-plate mist eliminator consists of two perforated metal sheets spot-welded together and uniformly spaced a few thousandths of an inch apart, with perforations in adjacent sheets offset so the air entering the holes in the first sheet impinges on the second sheet and must make two 90° turns before it can escape. Moisture is removed by impingement of droplets on the water film flowing down between the sheets and on the face of the first sheet. The efficiency for large drops (50 μm and larger) is virtually 100 wt %, and the efficiency for 1- to 10-μm droplets is greater than 99 wt % at air velocities of 500 to 600 fpm. The pressure drop is high, as shown in Fig. 3.21.

The base material is made in flat sheets, which can be welded edge to edge to form separators of any size and capacity. The material lends itself to pleating, as Fig. 3.21 shows, and can be formed easily into cones, cylinders, and other configurations (except com-

pound curves) to increase the surface area per square foot of frontal area. Experience shows that the units do not clog or flood easily, but they must be cleaned regularly to give satisfactory service. The plates can be cleaned in place by irrigation with acid or caustic solutions, flushing, and scraping (on the front plate). Separation of the plates can occur if the material is bent too sharply; a minimum radius of five times the metal thickness and a minimum saw-tooth angle (Fig. 3.21) of 45° is recommended for fabrication. The plates must be installed to allow water to flow off them easily. Saw-tooth configurations should be installed with the pleats vertical, and cones should be installed with the point up to avoid flooding. Cylinders should be vertical or installed on a steep slope.
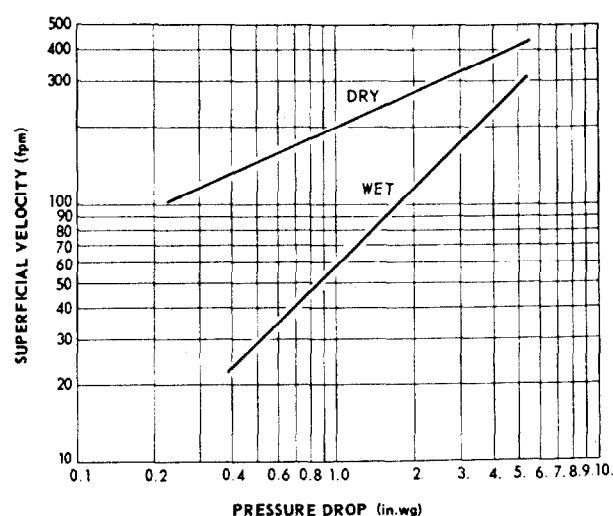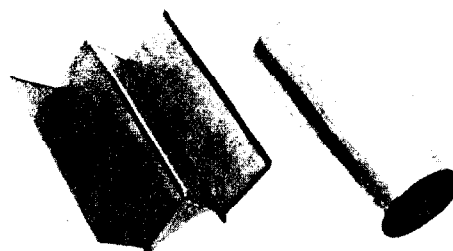

Fig. 3.21. Perforated-plate mist eliminator. Courtesy Multi-Metals. Inc.

Application. Both the packed-fiber and the perforated-plate mist eliminators have given satisfactory service in radiochemical operations, and both can be tailored to a wide range of corrosive conditions. The packed-fiber type is probably the better type where very high efficiency for small droplets at low flows is required. The perforated-plate type gives good service where flow rates are high and where extremely high efficiency for droplets smaller than about 5 μm is not required. Neither type is suited to reactor postaccident cleanup applications.

REFERENCES FOR CHAP. 3

1. IES-CS-1, *Standard for HEPA Filters*, Institute of Environmental Sciences, Mt. Prospect, Ill., 1968. All standards of the American Association for Contamination Control were adopted by IES when the two organizations merged in 1973.

2. Particle-collection efficiency is the measure of the number of particles captured by the filter, expressed as a percentage of the particle concentration of the unfiltered air.

3. "Filter Unit Testing and Inspection Service," *Environmental Safety and Health Information* bulletin, Energy Research and Development Administration, current issue.

4. The term dust is used to denote particulate material of all types trapped by the filter.

5. C. A. Burchsted, "Environmental Properties and Installation Requirements of HEPA Filters," *Proc. Symp. Treat. Airborne Radioact. Wastes*, International Atomic Energy Agency, Vienna, 1968.

6. Military Specification MIL-F-51079, *Filter Medium, Fire-Resistant, High Efficiency*.

7. W. L. Belvin et al., *Development of New Fluoride Resistant HEPA Filter Medium*, Final Report, ERDA Report TID 26649, Herty Foundation, Savannah, Ga., August 1975.

8. C. C. Wright et al., *The Evaluation of Substitutive Filter Framing Materials In Corrosive Environments*, USAEC Report K-TL-81, Union Carbide Corporation, Nuclear Division, May 19, 1970.

9. F. E. Adley, "Progress Report, Factors Influencing High Efficiency Gasket Leakage," *Proc. 9th AEC Air Clean. Conf.*, USAEC Report CONF-660904, 1966.

10. UL-586, *High Efficiency Air Filter Units*, Underwriters' Laboratories, Chicago, 2d ed. 1964.

11. NFPA 90A, *Standard for the Installation of Air Conditioning and Ventilation Systems Other than Residence Types*, National Fire Protection Association, Boston, 1968.

12. W. L. Anderson and T. Anderson, "Effect of Shock Overpressure on High Efficiency Filter Units," *Proc. 9th AEC Air Clean. Conf.*, USAEC Report CONF-660904, 1966.

13. Regulatory Guide 1.76, *Design Basis Tornado for Nuclear Power Plants*, U.S. Atomic Energy Commission, Washington, D.C., April 1974.

14. W. S. Gregory, *HEPA Filter Effectiveness During Tornado Conditions*, USAEC Report LA-5352-MS, Los Alamos Scientific Laboratory, 1973.

15. IES CS-1, *Standard for HEPA Filters*, Institute of Environmental Sciences, Mt. Prospect, Ill., current issue.

16. C. A. Burchsted, *Qualification Test for Moisture and Corrosion Resistant Separators for Air Filters*, Oak Ridge National Laboratory, 1965.

17. J. A. Geer, *Results of Testing of HF-Resistant Filters at Rocky Flats*, Report to the Joint Government-Industry Conference on Filters and Filter Media at the 13th AEC Air Cleaning Conference, San Francisco, Calif., August 1974.

18. L. R. Jones, "High-Efficiency Particulate Air (HEPA) Filter Performance Following Service and Radiation Exposure," *Proc. 13th AEC Air Clean. Conf.*, USAEC Report CONF-740807, 1975.

19. L. R. Jones, "Effects of Radiation on Reactor Confinement System Materials," *Proc. 12th AEC Clean. Conf.*, USAEC Report CONF-720823, 1972.

20. J. R. Gaskill and M. W. Magee, "The HEPA-Filter Smoke Plugging Problem," *Proc. 14th AEC Air Clean. Conf.*, ERDA Report CONF-740807, March 1975.

21. ASHRAE 52-68, *Method of Testing Air Cleaning Devices Used In General Ventilation for Removing Particulate Matter*, American Society of Heating, Ventilating, and Air-Conditioning Engineers, New York, 1968.

22. "Unit or Panel Type Air Filtering Devices," *Code for Testing Air Cleaning Devices Used in General Ventilation*, Air Filter Institute, Louisville, Ky., 1956.

23. *AFI Dust Spot Test Code*, Air Filter Institute, Louisville, Ky., 1960.

24. R. S. Dill, *A Test Method for Air Filters*, National Bureau of Standards, 1938.

25. UL-900, *Air Filter Units*, Underwriters' Laboratories, Chicago, current issue.

26. *Building Materials List*, Underwriters' Laboratories, Chicago, current issue.

27. ASTM D2652, *Standard Definitions of Terms Relating to Activated Carbon*, American Society for Testing and Materials, Philadelphia, current issue.

28. RDT M 16-1, *Gas-Phase Adsorbents for Trapping Radioactive Iodine and Iodine Compounds*, Energy Research and Development Administration, current issue.

29. ANSI N509, *Nuclear Power Plant Air Cleaning Units and Components*, American National Standards Institute, New York, 1976.

30. A. H. Dexter, A. G. Evans, and L. R. Jones, *Confinement of Airborne Radioactivity*, ERDA Report DP-1390, Savannah River Laboratory, October 1975.

31. D. A. Collins et al., *The Development of Impregnated Charcoals for Trapping Methyl Iodide at High Humidity*, TRG Report 1300(W), United Kingdom Atomic Energy Authority, London, 1967.

32. R. E. Ackley, Z. Combs, and R. E. Adams, *Aging, Weathering, and Poisoning of Impregnated Charcoals Used for Trapping Radioiodine*, USAEC Report ORNL-TM-2860, Oak Ridge National Laboratory, March 1970.

33. Regulatory Guide 1.52, *Design, Testing, and Maintenance Criteria for Atmospheric Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants*, U.S. Atomic Energy Commission, Washington, D.C., June 1973.

34. A. G. Evans and L. R. Jones, *Iodine Retention Studies - Progress Report: July 1970 - December 1970*, USAEC Report DP-1271, Savannah River Laboratory, 1971.

35. Letter, R. E. Adams to R. Herzel, Phillips Petroleum Co., reporting results of tests on charcoal samples removed from adsorbers of Carolina-Virginia Tube Reactor, Aug. 7, 1967.

36. Robert Blumberg, coordinating engineer for dismantling of Elk River Reactor, personal communication to C. A. Burchsted.

37. C. A. Burchsted and A. B. Fuller, *Design, Construction, and Testing of High-Efficiency Air Filtration Systems for Nuclear Application*, USAEC Report ORNL/NSIC-65, Oak Ridge National Laboratory, January 1970.

38. F. R. Schwartz, Jr., President of North American Carbon Inc., personal communication to C. A. Burchsted.

39. R. A. Lorenz, W. J. Martin, and H. Nagao, "The Behavior of Highly Radioactive Iodine on Charcoal," *Proc. 13th AEC Air Clean. Conf.*, ERDA Report CONF-740807, May 1975.

40. E. A. Bernard and R. W. Zavadoski, "The Calculation of Charcoal Heating in Air Filtration Systems," *Proc. 13th AEC Air Clean. Conf.*, ERDA Report CONF-740807, May 1975.

41. R. E. Adams et al., "Application of Impregnated Charcoals for Removing Radioiodine from Flowing Air at High Relative Humidity," *Treatment of Radioactive Wastes, Proceedings of a Symposium, New York, NY, August 26-30, 1968*, International Atomic Energy Agency, Vienna, 1968.

42. R. E. Adams and R. P. Shields, "Ignition of Charcoal Adsorbers by Fission Product Decay Heat," *ORNL Nuclear Safety Research and Development Program Bimonthly Progress Report for November–December 1967*, USAEC Report ORNL-TM-2095, Oak Ridge National Laboratory, February 1968.

43. J. L. Kovach and J. E. Green, "Evaluation of the Ignition Temperature of Activated Charcoals in Dry Air," *Nucl. Saf.* 8 (1966).

44. A. G. Evans, *Confinement of Airborne Radioactivity—Progress Report July 1972 to December 1976*, USAEC Report DP-1329, Savannah River Laboratory, 1973.

45. IES CS-8, *High Efficiency Gas-Phase Adsorber Cells*, Institute of Environmental Sciences, Mt. Prospect, Ill., current issue.

46. ASTM E11, *Standard Specification for Wire-Cloth Sieves for Testing Purposes*, American Society for Testing and Materials, Philadelphia, current issue.

47. V. R. Deitz and C. A. Burchsted, *Survey of Domestic Charcoals for Iodine Retention*, U.S. Navy NRL Memorandum Report 2960, Naval Research Laboratory, January 1975.

48. I. J. Gal et al., "Adsorption of Methyl Iodide on Impregnated Alumina," *Proc. 13th AEC Air Clean. Conf.*, ERDA Report CONF-740807, May 1975.

49. D. T. Pence et al., "Developments in the Removal of Airborne Iodine Species with Metal-Substituted Zeolites," *Proc. 12th AEC Air Clean. Conf.*, USAEC Report CONF-720823, January 1973.

50. *CRI-Nuclear Technical Data*, CTI-Nuclear, Inc. Bulletin N73-001, 1975.

51. J. G. Wilhelm and H. Schuettelkopf, "Inorganic Adsorber Materials for Trapping of Fission Product Iodine," *Proc. 11th AEC Air Clean. Conf.*, USAEC Report CONF-700816, December 1970.

52. Regulatory Guide 1.3, *Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Pressurized Water Reactors*, U.S. Atomic Energy Commission, Washington, D.C., June 1974.

53. A. G. Evans, "Effect of Intense Gamma Radiation on Radioiodine Retention by Activated Carbon," *Proc. 12th AEC Air Clean. Conf.*, USAEC Report CONF-720823, 1973.

54. T. D. Anderson, "The Holdup Effect of Double Reactor-Containment and its Influence on Dose from Airborne Radioactive Materials," *Proc. 8th AEC Air Clean. Conf.*, USAEC Report TID-7677, October 1963.

55. "Phase Separation," Chap. 19 in *Chemical Engineers Handbook*, 4th ed., McGraw-Hill, New York, 1963.

56. J. R. Murrow, *Plugging of High Efficiency Filters by Water Spray*, USAEC Report TID-4500, University of California, Lawrence Livermore Laboratory, 1967.

57. A. H. Peters, *Application of Demisters and Particulate Filters in Reactor Containment*, USAEC Report DP-812, Savannah River Laboratory, 1962.

58. L. R. Jones, "High-Efficiency Particulate Air (HEPA) Filter Performance Following Service and Radiation Exposure," *Proc. 13th AEC Air Clean. Conf.*, ERDA Report CONF-740807, March 1975.

59. Regulatory Guide 1.52, *Design, Testing, and Maintenance Criteria for Atmosphere Cleanup System Air Filtration and Adsorption Units of Light-Water-Cooled Nuclear Power Plants*, Nuclear Regulatory Commission, Washington, D.C., 1975.

60. G. H. Griwatz et al., *Entrained Moisture Separators for Fine Particle Water-Air-Steam Service; Their Performance, Development, and Status*, USAEC Report MSAR-71-45, MSA Research Corp., March 1971.

61. M. W. First and D. H. Leith, *ACS Entrainment Separator Performance for Small Droplet-Air-Steam Service*, Harvard Air Cleaning Laboratory Report 75-1106, Harvard University School of Public Health, Nov. 6, 1975.

62. R. D. Rivers and J. L. Trinkle, *Moisture Separator Study*, USAEC Report NYO-3250-6, American Air Filter Co., June 1966.

63. Registered trademark, E. I. du Pont de Nemours & Co.

64. A. G. Evans, Savannah River Laboratory, personal communication to C. A. Burchsted.

65. H. S. Dutcher, Air and Refrigeration Corporation, personal communication to C. A. Burchsted.

66. T. E. Wright et al., *High Velocity Filters*, USAF Report WADC 55-457, ASTIA Document No. AD-142075, Donaldson Company, Inc., 1957.

67. C. G. Bell and W. Strauss, "Effectiveness of Vertical Mist Eliminators in a Cross Flow Scrubber," *J. Air Pollut. Control Assoc.* 23, 967–69 (November 1973).

68. J. A. Brink, "Removal of Phosphoric Acid Mists," Chap. 5 in *Gas Purification Process*, George Newnes, Ltd., London, 1964, Part B.

69. J. A. Brink et al., "Mist Eliminators for Sulfuric Acid Plants," *Chem. Eng. Prog.* 64(11), 82–86 (November 1968).

70. G. A. Johnson, Atlantic-Richfield Hanford Co., personal communication to C. A. Burchsted.

71. J. A. Rauscher et al., "Fiber Mist Eliminators for Higher Velocities," *Chem. Eng. Prog.* 60(11), 68–73 (November 1964).